Eagle: Efficient Privacy Preserving Smart Contracts

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Abstract. The proliferation of Decentralised Finance (DeFi) and Decentralised Autonomous Organisations (DAO), which in current form are exposed to front-running of token transactions and proposal voting, demonstrate the need to shield user inputs and internal state from the parties executing smart contracts. In this work we present "Eagle", an efficient UC-secure protocol which efficiently realises a notion of privacy preserving smart contracts where both the amounts of tokens and the auxiliary data given as input to a contract are kept private from all parties but the one providing the input. Prior proposals realizing privacy preserving smart contracts on public, permissionless blockchains generally offer a limited contract functionality or require a trusted third party to manage private inputs and state. We achieve our results through a combination of secure multi-party computation (MPC) and zero-knowledge proofs on Pedersen commitments. Although other approaches leverage MPC in this setting, these incur impractical computational overheads by requiring the computation of cryptographic primitives within MPC. Our solution achieves security without the need of any cryptographic primitives to be computed inside the MPC instance and only require a constant amount of exponentiations per client input.

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1 Introduction

Ethereum introduced the first implementation of Turing-complete smart contracts for blockchains, widely adopted for financial and contracting applications since its introduction in 2015. Smart contracts offer auditability and correctness guarantees, and as a consequence expose both their state and any submitted inputs to all participants of the blockchain network. This lack of privacy not only leaks user data but also gives rise to concrete attacks. For example, current Decentralised Finance (DeFi) and Decentralised Autonomous Organisations (DAO) are vulnerable to front-running [30] in token transactions and proposal voting. This motivates the need to shield user inputs and internal contract state from the very parties who execute smart contracts in a decentralized environment.

Challenges. Hawk [54] introduced the first notion of general-purpose privacy preserving smart contracts, which required users to privately submit both input strings and confidential balances to a trusted contract manager. Upon evaluation of the contract over private inputs, the contract manager settles the confidential outputs to a confidential ledger, proving in zero knowledge that these outputs have been obtained according to the contract's instructions. Importantly, in order to accommodate real-world applications such as DeFi or DAO's, we must extend the Hawk notion of confidential contracts as follows:

1. Distribute the role of the trusted third party in an efficient manner, avoiding a single point of failure without significantly sacrificing performance.
2. Only require clients to be online during a short input phase; as in the standard client-blockchain interaction model, clients only broadcast signed inputs.
3. Allow privacy preserving smart contracts to be long-running applications over indefinite rounds, as is the case in standard, public smart contracts.

Our Contributions. In this work we present "Eagle", a Universally Composable [22] protocol for achieving efficient privacy preserving smart contracts, which handles all the three challenges explained above: (1) is achieved by evaluating the contract's instructions via an *outsourced* secure multi-party computation (MPC) protocol [44], where clients provide private inputs and servers execute the bulk of the protocol to compute a function on these inputs without learning them. We use a MPC protocol, known as *insured MPC*, which allows a public verifier to identify servers aborting at the output phase, so that cheating servers can be identified and financially punished, incentivizing fairness (*i.e.* if a server gets the output, all servers/clients also get it) [9]. That is, by combining outsourced and insured MPC we get a protocol where client computation and interaction is independent of the circuit computed in MPC and where *reliability* is incentivized and *security* is obtained as long as only a single MPC is honest. (2) is accomplished with a novel input protocol which pre-processes data necessary for the servers to generate private outputs (*e.g.* token amounts) that are posted directly to the public ledger but can only be read by specific clients. (2) facilitates (3), realized by a *reactive* version of our MPC protocol, which maintains a secret off-chain state over multiple rounds. Here, we contribute a model

of long-running, privacy preserving contracts, which at the onset of each round accepts new inputs from any subset of clients. At the end of each round, clients get public outputs and servers keep a secret internal state, allowing evaluation to take place in a continuous, *multi-round* fashion, even if clients are offline (2).

In the recent years decentralized cryptocurrency has gained more traction and multiple new tokens with their own associated blockchain and Turing complete smart contract languages have sprung up. This has led to the development of new financial instruments leveraging the value of these tokens and the automation and guaranteed correctness offered by smart contracts. The tools and products in this generally referred to as *DeFi*; short for decentralized finance. This allows for public audibility, efficient and guaranteed correct execution, compared to the traditional financial markets of Wall Street. While DeFi has been a main driving force in the blockchain space lately, another use-case leveraging the blockchains' features, which is gaining traction, is decentralized identity management. In such a system certified attributes about the users are stored securely on a blockchain and allow users to prove certain attributes about themselves, both in the real-world, web 2 and web 3 space [61]. Yet another prominent case is voting; both in relation to Decentralized Autonomous Organizations (DAOs) and governance within the blockchain space, but also in the setting of real world elections as well [47].

However, one common feature of these use-cases (in particular the latter ones) is that they require a notion of anonymity and privacy and hence public auditability becomes a double edged sword. Consider for example smart contracts that need to compute on open order information in the case of DeFi, personal data, such as emails or health information, in the case of decentralized identity management, ballot information in case of voting and high entropy cryptographic information such as private keys in general when integration with other cryptographic systems are required. Much research [54, 74, 11, 17] have been carried out in the space of adding privacy to smart contracts. In fact, blockchains dedicated to private smart contracts has spurred up, such as the Partisia Blockchain.

Even so, hiding the data to be computed on, is not necessarily all that is needed to facilitate many of the applications of blockchain technology. In particular, in DeFi, the amounts of tokens going into and out of smart contract, can be considered private. This is for example the case in auctions facilitated by a smart contract, where users wish to bid for a digital item by transferring tokens to an auction smart contract. However knowing the other users' bid will of course allow a rushing adversary to always win a first-price auction by simply observing all other bids and bit one above that. A more subtle situation where hidden token amounts are crucial is in the exchange setting. Consider a user who wish to issue a limit order through a smart contract, facilitating exchange between two tokens on behalf of multiple peers. In such a case both the limit order specification, along with the amount the user wishes to exchange can be objectively considered private. Even worse, in such situations, if the token amounts being exchanged are public, it can allow miners to make a profit by

doing *front-running* [30]. For example a miner who sees a very large transaction that would change the market value of one token against another, could chose to drop this order and instead inject an order, knowing that they are guaranteed to be make to make a profit in the next block, when the large order gets completed. This can even be achieved without dropping order, by simply injecting an order and reordering the rest, such that the exchange rate computed by a smart contract gets manipulated through the execution of the block, to allow the miner to make a profit. Such front-running by miners on the blockchain is know as Miner Extractible Value (MEV). Because of these problems, multiple layer 1 blockchains aim to hide token quantities. Such as ZCash through the use of SNARKs [12], Monero through ring signatures [53], and Dash through mixnets [36]. Several layer 2 solutions have also been proposed. For example, Zether through the use of commitments and BulletProofs [18], Zexe through SNARKs and commitments on top ZCash [17], Hawk through SNARKs and commitments on arbitrary chains but requires a trusted third party [54], Veksel also through SNARKs and commitments, along with accumulators [21].

While the issue of privacy preserving smart contracts, hiding token amounts, inter-chain communication and decentralized cross-chain transfers have all been solved efficiently on their own, a system affording *all* of these together has to the best of our knowledge remained elusive.

Applications. Several general applications for privacy preserving smart contracts have already been proposed. **Auctions:** can be realized securely on-chain with privacy preserving smart contracts, as auctions implemented without privacy are vulnerable to front-running (miners can trivially observe individual bids posted to the ledger). **Identity management:** Decentralized Identity (DID) management considers the setting where user-attributes are posted to a ledger, in a certified, yet hidden manner. DID implemented with privacy preserving smart contracts enables proofs and computations on private identity attributes, facilitating their integration with blockchain applications. **KYC Mixing:** We can construct a privacy preserving smart contract to realize a mixer that enforces Anti Money Laundering (AML) policies. For example, such a mixer could use DID to integrate Know Your Customer (KYC) information to either limit user permissions or the quantity of mixed tokens allowed per month. **Side-chains:** The MPC servers alone could be considered a privacy preserving side-chain. Multiple sets of MPC servers could work together with a single smart contract to realize a privacy preserving sharding scheme on any layer 1 chain with Turing complete smart contracts. **AMMs and DeFi via Cross-chain contracts:** Using ideas of P2DEX [11], we show that the MPC servers can interact with smart contracts on many different ledgers. Hence, privacy preserving smart contracts can work *across* multiple ledgers and different native tokens. This realizes cross-chain, front-running resistant automated market makers (AMMs) with strong privacy guarantees. We discuss these applications in more detail in Appendix D.

Our Techniques. We sketch our protocol in Fig. 1. This only considers execution of a *single* instance of a privacy preserving smart contract for simplicity. We

discuss the multi-round setting in Sec. 3.2 where computations are executed continuously with different sets of clients. We assume a set of clients $\mathcal{C}$ and MPC servers $\mathcal{P}$, both interacting with a ledger functionality $\mathcal{F}_{\mathsf{Ledger}}$. The ledger hosts two deployed smart contract instances: $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ maintains a confidential ledger and is extended with $\mathcal{X}_{\mathsf{Lock}}$, which locks and redistributes confidential balances, output and jointly signed, by the MPC servers. Concretely our protocol runs the following phases:

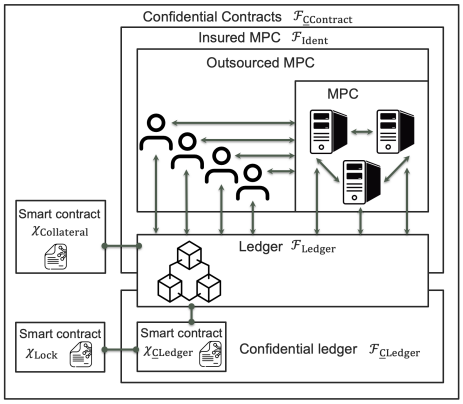


Fig. 1: Outline of our protocol for confidential contracts. The wrapping and interaction of functionalities are shown.

Init Before any execution, the servers setup the system by sampling a threshold signature key pair and provide sufficient collateral for the insured MPC execution, and setup smart contact $\mathcal{X}_{\mathsf{Lock}}$, administered by the distributed signature key. We note that in the multi-round setting this only needs to be executed *once* for the specific set of MPC servers, and is thus independent of the clients and the amount of computations that will get carried out later.

Enroll When a privacy preserving smart contract is to be executed, each client who wish to participate transfers confidential tokens to $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ which they wish to use as input to the confidential smart contract $\underline{\mathsf{C}}\mathsf{Contract}$. The client then gives any auxiliary input, along with the opening information to the commitment containing their confidential balance v, to the insured MPC functionality $\mathcal{F}_{\mathsf{Ident}}$ from Fig. 6, extended with a secure client input interface (See Appendix A.1). Each client constructs an appropriate amount of "mask" commitments; one for each round of confidential contract computation, for which they wish their input to be used. A masking commitment is simply a commitment to a random value.

Verify input The servers validate the input received from the clients using outsourced MPC, and ensure that $\mathcal{X}_{\mathsf{Lock}}$ has also received the appropriate confidential tokens. The servers and the clients also execute a proof to ensure that the opening information supplied by clients are indeed valid for the confidential token commitments. They do this following a standard Σ-protocol where each client commits to a random commitment a and servers select a random challenge γ and ask the client to open $\mathrm{com}(c) = \mathrm{com}(a) \oplus (\gamma \odot \mathrm{com}(v))$. Similarly the servers use MPC to securely open $[c] = [a] + \gamma \cdot [v]$ and check consistency[4].

[4] In our full protocol we optimize this by batching client input checks.

Evaluate After the checks are completed the servers evaluate the circuit expressing the private smart contract $\underline{\mathsf{C}}\mathsf{Contract}$, using insured MPC. For the clients who are supposed to get output from this round of computation, shares of messages and randomness for a new commitment for *each* client are computed, and blinded with the "masking" values the clients provided during *Enroll*. If this goes well, the servers distributedly sign a message saying that they have reached this stage and post it to $\mathcal{X}_{\mathsf{Lock}}$.

Open For clients that receive output after this round of computation the servers open the masked output. They publish these values and sign them, as part of the transcript of the current round execution, and post this to $\mathcal{X}_{\mathsf{Lock}}$. Note that $\mathcal{X}_{\mathsf{Lock}}$ can generate the output coins in commitment form, due to the homomorphism of the commitments and since it obtained the mask commitments from the clients in *Enroll*. $\mathcal{X}_{\mathsf{Lock}}$ can then transfer the new confidential tokens back to the client's address. We show an extension to our protocol (3.2) that ensures no token minting can occur even if all servers are corrupted.

Withdraw Based on the masks they constructed, the clients who are supposed to receive outputs can compute the coin commitment openings from their masked outputs signed and posted to $\mathcal{X}_{\mathsf{Lock}}$ by servers during *Open*.

Abort In case a server stops responding or acts maliciously, an honest server can request the entering of an abort phase. Any server can do this, either by submitting a proof that the malicious server sent wrong information or by requesting missing information from the accused servers. At this point the accused malicious server has a constant amount of time left to prove to the smart contract that they did not abort, by submitting the message that the accusing server claims they didn't get. If they don't, they will have their collateral revoked and it will be shared among the honest servers and clients, and the contract state will roll back one round, i.e. to the contract state preceding *Evaluate*. Concretely $\mathcal{X}_{\mathsf{Lock}}$ will refund the clients their input funds, plus a compensation obtained from the cheating servers' collateral.

1.1 Related Works

Privacy preserving transactions. The notion of confidential tokens was first proposed by Maxwell in [62], and subsequently formalized in [68]. Here, balances are concealed in additively homomorophic Pedersen commitments [67]. A valid transfer consumes and produces new commitments and is accompanied by a non-interactive range-proof [19] that each newly coin balance is below a threshold preventing the minting of tokens. Thus, if input and output commitments sum up, the ledger can verify that the coin supply was preserved. ZCash [12] breaks any relation between spent and newly minted tokens with general zkSNARK's proving both balance ranges and that confidential input coins have not previously been spent. Subsequent works [21] have improved on the complexity of NIZK's required. Zether [18] proposes a scheme which can be implemented on any public ledger with EVM-like smart contract machine, encrypting user balances with additive Elgamal encryption: importantly, for smaller balance ranges,

this scheme permits the receiver to obtain the *opening* of privately received coins by brute-forcing an discrete-logarithm. Thus, unlike in other schemes, a sender does not need forward the private coin opening to the receiver. A weaker notion of privacy is achieved by Monero [70, 65], which offers k-anonymity for senders.

Privacy preserving smart contracts (PPSC):. We outline a long line of work which realizes notions of privacy preserving smart contracts; these approaches sacrifice privacy [54, 74, 45, 59, 50, 75, 73, 27] or flexibility [17, 18].

PPSC for ZCash: Zexe [17] extends the ZCash model of private transactions with a private, state-less contract model. Bitcoin Script-like contracts are hidden, as are contract inputs, enabling limited contracting functionality with privacy. Furthermore, Zexe requires the execution of a trusted setup phase for *each* application. However, this need was removed in the follow-up VeriZexe [79].

PPSC with (F)HE: Zkay [74] allows for computing on encrypted private inputs by means of keeping data encryption on the blockchain, and using NIZKs to validate that any updates done to the encrypted is carried out correctly. Follow-up work, Zeestar [73] uses additively homomorphic encryption to allow for *limited* private computation on data from multiple owners, without them having to share their private data with each other. SmartFHE [72] on the other hand uses FHE and NIZKPs construct a blockchain with support for privacy preserving transactions and general privacy preserving smart contracts. Their idea is to have each user setup an FHE scheme associated with their account. Every time they use the tokens in their account, they use the FHE scheme to perform the needed computation on their tokens and any auxiliary input and prove in zero-knowledge this was done correctly, before posting everything to the blockchain, for verification by a miner. Unfortunately this is rather inefficient, as simply validating a private transactions takes a miner more than 9 seconds. Furthermore, to compute fully private smart contracts with inputs from multiple parties they are required to expand their encrypted input to be encrypted under all public keys of the clients giving input to the smart contract. Thus requiring online interaction between all the clients with relevant data to the computation. Furthermore, in general this line of work does not explicitly provide privacy between contract participants, as a party which holds the encryption key can trivially observe the contract evaluation in the clear.

PPSC with TEE: Secret Network [75] and Ekiden [27] implement general purpose contracts but rely on notoriously vulnerable trusted execution environments (*e.g.* Intel SGX [64]) for privacy and correctness. Arbitrum [45] relies on a full quorum of parties (the servers in our setting) being honest to achieve privacy for general purpose contracts.

PPSC with input concurrency: Finally, Kachina [50] subsumes these approaches with a framework based on state oracles [59] that yields privacy preserving smart contracts, where either flexibility is limited (*i.e.* contract state is only updated by one client's private input at a time) or privacy is compromised (*i.e.* a trusted third party must learn clients' private inputs in order to update the state). The ideal functionality of Kachina is designed to permit *input concurrency*, allowing honest inputs to be finalized on a global ledger in a different

order as their generation; the Kachina protocol requires private inputs to be accompanied with NIZKs proving a valid update of the private state fragment. Here, the NIZKs are not bound to a specific, public contract state and thus remain valid even if the public contract state observed by the user was updated by another user input in the meantime.

PPSC with MPC: Combining MPC with blockchain based cryptocurrencies and smart contracts has been investigated in a long line of works [3, 4, 14, 56, 55, 57, 52, 28, 15, 13, 34, 9, 11, 10] aiming at achieving fairness in the dishonest majority setting via financial punishments. The core idea of these works is having all parties, who execute the MPC protocol, provide a collateral deposit, which is taken from them in case they are caught cheating. Thus incentivizing honest behavior. However, this approach publicly reveals the amount of collateral deposited by each party, which falls short of achieving our notion of privacy preserving smart contracts, where both auxiliary data *and* the amount of tokens given as input to the contract must remain private. Notice that revealing the deposit amount is an issue in applications where this amount is directly related to the client's private input, *e.g.* in sealed-bid auctions, where the collateral deposit must be equal to at least the client's private bid. An auction protocol using collateral deposits with private amounts was proposed in [35] but it cannot be generalized to other tasks.

Hawk [54, App. G] does suggest to use MPC to achieve a decentralized confidential smart contracts on both token amount and auxiliary input. However, Hawk works in the ZCash model and thus their MPC solution would require the computation of SNARKs to realize the ZCash transactions, within the MPC circuit. Although it has been shown [66, 46] that integrating NIZKs with MPC can be done without degrading performance too much, there is still a performance hit. Since the construction of a single ZCash transaction SNARK still takes a non-negligible amount of time plain, this would naturally be inefficient to realize in MPC, as MPC is orders of magnitude slower than regular computation. Furthermore, they need *all* users to take part in the MPC computation. The recent work zkHawk [6] improves upon this, by forgoing the need of doing SNARKs in MPC, but still require *all* users taking part in a confidential smart contract to facilitate an MPC computation which *must* compute Schnorr style ZKPs on Pedersen commitments to the bit-decomposition of the amount of coins each of them hold. While follow-up V-zkHawk [7] forgoes the need of proofs of the bit-decomposed commitments, they replace it with the computation of commitments in a larger fields and a signature, in MPC instead. While more efficient, this approach would still require MPC over a large domain and contributes non-negligible overhead. Recently, Kanjalkar *et al.* [46] present an optimized ZK protocol to be proven inside MPC.

P2DEX At ANCS 2021 Baum *et al.* [11] introduced P2DEX, which extends Insured MPC [9] by allowing for cross-chain communication and privacy preserving smart contract computation. Although their privacy preservation only involves auxiliary input, and *not* the token amounts. Their idea is to first have user send the tokens to a burner address, generated in a distributed manner by a

set of servers. These servers then run an Insured MPC protocol which computes a private smart contract based on auxiliary input privately given by the users. Based on the result, appropriate amount of tokens can be transferred from the burner addresses to the users by having the servers threshold sign these transactions. The authors use this to make a system for decentralized cross-chain exchange, preventing *both* miner and operator front-running.

Fair MPC with public ledgers. We describe two closely related lines of work that integrate MPC protocols with a ledger functionality to achieve (1) fair MPC protocols, which identify and penalize cheating parties and (2) private smart contracts executed inside a MPC instance which finalize the *confidential* outcome on the ledger.

The first works to utilize the Bitcoin ledger to achieve fairness in lottery games was introduced in [3, 4], where cheating parties can abort upon learning the output first but incur a financial penalty without requiring a trusted party to arbitrate. This notion of output fairness was generalized to any secure function evaluation by Bentov *et al.* [14] and to the reactive setting [56]. Subsequent works improve the efficiency of output fairness [55, 57, 15, 13, 34], culminating in Insured MPC [9], which formulates a UC-secure MPC functionality with identifiable aborts. Another line of work [52, 28] focuses on stronger notions of fairness, identifying aborting parties' prior to the output phase.

In this work we present a protocol for Privacy Preserving Decentralized Smart Contracts ("NAME"). Our system supports privacy preserving computation on *both* token amounts and *auxiliary* input. Our scheme has been designed to allow for minimal user interaction and only requires a lightweight user-client only needing a constant amount of rounds of communication and is agnostic to all other user-clients.

Our core contribution is a UC-secure protocol for privacy preserving contracts, hiding both data and token amounts. The overall idea of our scheme is to have a set of servers run a continuous dishonest majority, maliciously secure Multi-Party Computation (MPC), in discrete rounds. During each round, users can supply hidden input and hidden tokens to the MPC system, which will then compute a publicly known computation on the hidden input and tokens and redistribute private information and tokens accordingly based on the computation. The user don't need to be online at the end of the computation as their private output will be encrypted and can thus be publicly distributed to any untrusted server or blockchain, where the users can retrieve it at their convenience.

To facilitate hidden token amounts in a way that can integrate with the MPC system, we use a scheme similar to Zether [18], where native tokens can be exchanged to hidden equivalents through a smart contract on the native chain. These hidden tokens are then modeled as NFTs that can be combined or split, through the help of a smart contract. Thus providing a layer 2 solution to hidden tokens. However, unlike Zether our layer 2 solution work in the UTXO model and models hidden token amounts as NFTs, consisting of Pedersen commitments. This allows users to manipulate these and transfer ownership, although the randomness used in the commitment is needed to use the tokens. Thus users

can transfer ownership of these to a smart contract administrated by the MPC servers and distribute opening information to the servers as as input to an MPC computation. This allows the servers to securely compute on the amounts and appropriate distribute new hidden tokens after a round of execution, though the layer 2 smart contracts. Even if all servers are malicious our layer 2, hidden token scheme remains secure and free from malicious minting or burning.

As long as just a single server is honest, then our system remains secure from theft. While a single malicious server *can* cause a roll-back of a given round. Although they are financially incentivized not to do so, though an ante stored in a smart contract, which can only be retrieved if all servers agree. We facilitate this through the Insured MPC approach of Baum *et al.* [9].

We also discuss how our solution can be extended to facilitate privacy preserving cross-chain communication and how this can be used do privacy preserving cross-chain exchange in a front-running preventing manner. This is inspired by the work of P2DEX [11], but with the added benefit of hiding token amounts.

1.2 Overall idea

Our core construction is a global UC-secure protocol running between a relatively small set of servers, which an adversary may actively corrupt a dishonest majority of, and a possibly large set of clients which the adversary may corrupt *any* amount of. Our construction assumes hybrid access to a global UC clock and ledger functionality (with Turing complete smart contracts), along with UC secure standard and distributed signature functionalities, a MPC scheme UC-secure against static and active corruption of a dishonest majority of the parties.

Our core protocol consists of two parts; 1) a layer 2 hidden token solution, facilitated on-chain through a smart contract which we denote $\underline{\mathsf{C}}\mathsf{Ledger}$ and fully decentralized off-chain through a secure and authenticated channel between peers, inspired by Zether [18] and 2) a private computation mechanism that can work over these hidden tokens and auxiliary input.

Hidden tokens. For the hidden token solution we get inspiration from Zether [18] which uses an account model where additive Elgamal is used to encrypt users' account balances, and non-interactive range proofs over these to prevent minting. However our scheme differs from Zether in two important points: 1) We move to using the UTXO model instead of accounts which frees us from handling several issues of transfer concurrency and front-running, and thus more simply integrate the confidential tokens with our MPC servers. 2) We use Pedersen commitments instead of additive Elgamal encryption. While using Elgamal encryptions make it possible for a user to decrypt their account balance without auxiliary information. It does require them to do it in a brute-force manner over the space of possible balances. For balances represented by 64 this border non-feasibility. Although Pedersen commitments require auxiliary information, shared off-chain, they can be constructed at half the size of Elgamal encryptions, and hence when working in the UTXO; size becomes much more critical.

More concretely we represent v confidential tokens are as an NFT of Pedersen commitment to v. In order to mint an NFT of v confidential tokens, a user will transfer v tokens to the smart contract and call a method MINT with a Pedersen commitment to v and a non-interactive zero-knowledge proof that the commitment is correctly constructed and holds the value v. The contract then validates the proof and mints an NFT based on this commitment and transfers it to the user. In order to redeem hidden tokens a user sends an NFT of v tokens to the smart contract, along with with call to the method REDEEM, with the opening information of the Pedersen commitment as parameters. The smart contract then validates the opening and transfer v tokens to the user. In order to actually use the hidden tokens and make transfers to other clients, we need to facilitate a way of combining and splitting NFTs. We do this through a method CONFTFR which takes two NFTs held by the transferring user, and new Pedersen commitments, constructed by the transferring user. The sum of the NFTs the transferring user holds and the new Pedersen commitments must be equal. The smart contract validates this through a zero-knowledge proof, also supplied by the transferring user. This is unfortunately not enough and the user also supplies a range proof that each of the two new Pedersen commitments are correctly constructed and contains values less than Max, for some maximum allowed amount of tokens. After validating both proofs the smart contract the mints NFTs based on these commitments and transfers the first NFT to the transferring user and the second one to the recipient. The transferring user must then send the opening information of the second Pedersen commitment to the recipient.

Private smart contracts. By executing public contracts in MPC, but on hidden input and tokens, we can realize the computation of an arbitrary private smart contract, which we call ConfContract. General, private input, is given to the servers using outsourced MPC and the execution of ConfContract is administered through a regular, native smart contract, extending the confidential tokens contract CLedger, which we call Lock. Concretely Lock facilitates public audibility of the whole process and allows recovery in case one or more servers misbehave. In a similar manner to P2DEX [11], we work in model where up all but one server can be maliciously corrupted. But to incentivize the servers to behave honestly using insured MPC [9]. Lock is initialized with a public key for a distributed signature scheme, for which the servers hold shares of the signing key. The contract will store all the confidential tokens during the MPC execution which clients want to compute on. Whereas the MPC servers will learn the opening information to the commitments that represents the clients' confidential tokens, through outsourced MPC. Thus, once the confidential tokens have been transferred to Lock and the MPC servers have shared of the openings to these and any auxiliary private input they compute the confidential smart contract. This computation will also give servers shares of the new distribution of confidential tokens between the client's who provided input. Based on these shares they can construct appropriate Pedersen commitments. The MPC servers then signs the transcript of the computation and new Pedersen commitments using

the distributed signing key and send this to ConfContract. The smart contract then validates the signature and burns the confidential tokens it holds and mints new ones according to the specification by the servers.

2 Preliminaries

Let $y \leftarrow\!\!\$\ F(x)$ denote running the randomized algorithm F with input x and implicit randomness, and obtaining output y. Similarly, $y \leftarrow F(x)$ is used for a deterministic algorithm. For a set $\mathcal{X}$, let $x \leftarrow\!\!\$\ \mathcal{X}$ denote x chosen uniformly at random from $\mathcal{X}$. s denotes the computational and κ the statistical security parameter. Let $[\,x\,]$ denote secret x maintained in an MPC instance: we lift the $[\,\cdot\,]$ notation to any object that can be encoded over secrets securely input to an MPC scheme, e.g. $[\,g\,]$, where g is an arithmetic circuit over field $\mathbb{F}$. We use a group $\mathbb{G}$ where the discrete log problem is hard, and which is a source group of pairing scheme. For simplicity we assume $|\mathbb{G}| = |\mathbb{F}| = p$. Unless noted otherwise we use log to denote the logarithm to base 2, rounded up. We use $\bar{v}_{\mathsf{max}}$ to denote the maximum amount of tokens we want to represent and say $l = \log(\bar{v}_{\mathsf{max}})$. For simplicity, we assume $|\mathcal{C}| \cdot \bar{v}_{\mathsf{max}} < |\mathbb{G}|$, where $\mathcal{C}$ is the set of participating clients. We denote set $\{1, 2, \ldots, n\}$ by $[n]$ and vectors by bold faced Latin letters, e.g. $\mathbf{v}, \mathbf{w}$.

Table 1: Notation.

$\mathcal{P}$	The set of servers.
$\mathcal{C}$	The set of clients.
n	Number of servers $n = \|\mathcal{P}\|$.
m	Number of clients; $m = \|\mathcal{C}\|$.
l	Number of bits representing balances.
z	Number of input/output per client.
κ	Computational security parameter.
s	Statistical security parameter.
$\mathcal{F}$	An ideal functionality.
Π	A protocol.
$\mathcal{L}$	A ledger map indexed by vk.
$\mathcal{X}$	A smart contract program.
g	A smart contract in circuit form.
vk	A public key for signature verification.
x	A client input.
y	A client output.
$\bar{\mathbf{v}}$	A token balance.
$\bar{v}_{\mathsf{max}}$	The maximum permitted balance.
$\bar{\mathbf{v}}_{\mathsf{max}}$	A vector of the maximum permitted balance.

2.1 Security Model and Building Blocks

We analyse our results in the the (Global) Universal Composability or (G)UC framework [23, 25]. We consider static malicious adversaries. Our protocols work in a synchronous communication setting, which is modeled by assuming parties have access to a global clock ideal functionality $\mathcal{F}_{\mathsf{Clock}}$ as seen in multiple works [5, 48, 52]. The core component of our protocols is publicly verifiable MPC with cheater identification in the output phase, which is modelled as an ideal functionality $\mathcal{F}_{\mathsf{Ident}}$, which can be realized as described by Baum *et al.* [9, 11]. This functionality produces a proof that either a certain output was obtained after the MPC or that a certain party has misbehaved in the output phase, while cheating before the output phase causes an abort without cheater identification. We further extend this functionality to handle reactive computation [33, 32] and an *outsourced* computation with inputs provided by clients and computation done by servers [44, 31]. Moreover, we use Pedersen Commitments [67], digital signatures represented by an ideal functionality $\mathcal{F}_{\mathsf{Sig}}$ as in [24], threshold signatures represented by an ideal functionality $\mathcal{F}_{\mathsf{TSig}}$ as defined by Baum *et al.* [11] and non-interactive zero knowledge proofs represented by $\mathcal{F}_{\mathsf{NIZK}}$ as defined by

Groth [43]. Further discussion on our security model and building blocks is presented in Appendix A.

2.2 Ledgers & Smart Contracts

We model a ledger functionality $\mathcal{F}_{\mathsf{Ledger}}$ in Appendix B.1 featuring a smart contract virtual machine which is adapted from an authenticated, public bulletin board functionality, an approach adopted from the work of Baum *et al.* [9, 11]. For this work, we emphasize accurate modelling of confidential balances, which are implemented on a public ledger, and omit the full consensus details in our UC model, similar to previous works [52, 5].

Token universe. $\mathcal{F}_{\mathsf{Ledger}}$ supports a token universe consisting of t token types: $\mathbb{T} = (\tau_1, ..., \tau_t)$. A ledger in $\mathcal{F}_{\mathsf{Ledger}}$ maintains a map from signature verification key to balances of each token type: $\mathcal{L} : \{0,1\}^* \rightarrow \mathbb{Z}^t$. We write $\bar{\mathbf{v}} = (v_1, ..., v_t)$ for a balance over all supported token types. In addition to balances associated to signature verification keys, $\mathcal{F}_{\mathsf{Ledger}}$ also maintains token balances for each deployed smart contract instance. The ledger functionality enforces the preservation of token supplies over $\mathbb{T}$.

Overview of smart contracts. In this work, we present smart contracts as human-readable programs and assume the presence of a compiler which translates program $\mathcal{X}$ to a valid circuit T and initial state γ_{init}. The following smart contract programs are deployed in the protocol which realizes the proposed confidential contract functionality $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$.

- $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ (Figure 11) describes a smart contract which implements a confidential token wrapper for each token in $\mathbb{T}$ supported on the base ledger $\mathcal{F}_{\mathsf{Ledger}}$.
- $\mathcal{X}_{\mathsf{Lock}}$ (Figure 14) is an extension to $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$. It permits the locking and redistribution of confidential balances authorized by verifying threshold signatures generated by the servers (via global functionality $\mathcal{F}_{\mathsf{TSig}}$).
- $\mathcal{X}_{\mathsf{Collateral}}$ (Figure 15) accepts collateral deposits from servers, which upon being identified as cheating parties lose their collateral to clients.

2.3 Confidential ledgers from $\mathcal{F}_{\mathsf{Ledger}}$

We briefly describe a confidential ledger functionality $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$, presented in full detail in Appendix B.2, that can be implemented from a hybrid $\mathcal{F}_{\mathsf{Ledger}}$ functionality, enabling both confidential balances and the confidential transfer of default tokens types $\mathbb{T}$ exposed by the underlying public ledger $\mathcal{F}_{\mathsf{Ledger}}$. This modeling choice maximizes the generality of our construction, as it can be implemented on any standard ledger and a basic smart contract machine.

Confidential ledger. Confidential coins in $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ are identifiable by a unique public id, and a confidential balance $\bar{\mathbf{v}}$ over $\mathbb{T}$, as in [68]. Each confidential token is publicly associated with an account verification key vk, owned by a party that generated it with GenAcct. A confidential transfer consumes two input

coins $(\mathsf{id}_1, \mathsf{id}_2)$ with confidential balances $(\bar{\mathbf{v}}_1, \bar{\mathbf{v}}_2)$ and mints fresh output coins $(\mathsf{id}'_1, \mathsf{id}'_2)$ with confidential balances $(\bar{\mathbf{v}}'_1, \bar{\mathbf{v}}'_2)$, such that $(\bar{\mathbf{v}}_1 + \bar{\mathbf{v}}_2 = \bar{\mathbf{v}}'_1 + \bar{\mathbf{v}}'_2)$. Here, coin id'_1 is now held by the owner of the receiving account, who also learns the confidential amount $\bar{\mathbf{v}}'_1$.

Functionality $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ exposes MINT and REDEEM interfaces: a mint activation *locks* a public amount of tokens $\mathbb{T}$ and generates a fresh confidential token of the same balance. Conversely, a redeem activation will *release* the balance of a confidential coin back to the public ledger.

Realizing a confidential ledger. A confidential token is realized in protocol $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$ described in full detail in Appendix C.1 with Pedersen Commitments [67]. Let $g, g_1, ..., g_t, h$ denote generators of group $\mathbb{G}$ of safe prime order p, such that s_i in $g_i = g^{s_i}$ and w in $h = g^w$ are given by $\mathcal{F}_{\mathsf{Setup}}$ (parameterized with $g \in \mathbb{G}$) that publicly outputs $g_1, ..., g_t, h$. The commitment to a balance $\bar{\mathbf{v}} = (v_1, ..., v_t)$ over tokens $\mathbb{T}$ with blinding r is $\mathsf{com}(\bar{\mathbf{v}}, r) = \mathbf{g}^{\bar{\mathbf{v}}} h^r = g_1^{v_1} ... g_t^{v_t} h^r$. Pedersen commitments are additively homomorphic: $\mathsf{com}(\bar{\mathbf{v}}_1, r_1) \circ \mathsf{com}(\bar{\mathbf{v}}_2, r_2) = \mathsf{com}(\bar{\mathbf{v}}_1 + \bar{\mathbf{v}}_2, r_1 + r_2)$. Thus, during a confidential transfer, the sum equality between consumed input and freshly constructed output coin commitments holds if total token balances are preserved and r'_1 and r'_2 are correlated such that $r_1 + r_2 = r'_1 + r'_2$.

$$\mathsf{com}(\bar{\mathbf{v}}_1, r_1) \circ \mathsf{com}(\bar{\mathbf{v}}_1, r_1) = \mathsf{com}(\bar{\mathbf{v}}'_1, r'_1) \circ \mathsf{com}(\bar{\mathbf{v}}'_2, r'_2) \tag{1}$$

However, since the equality above holds for any $\bar{\mathbf{v}}_1 + \bar{\mathbf{v}}_2 \equiv \bar{\mathbf{v}}'_1 + \bar{\mathbf{v}}'_2 \mod p$ and correlated r'_1, r'_2, an additional p units of each token in $\mathbb{T}$ can be minted: $\bar{v}_1 + \bar{v}_2 + p \equiv \bar{v}'_1 + \bar{v}'_2 \mod p$. Thus, each confidential token is associated with NIZK π which proves $\mathcal{R}(c; \bar{\mathbf{v}}, r) = \{c = \mathsf{com}(\bar{\mathbf{v}}, r) \wedge \bar{\mathbf{v}} \leq \bar{\mathbf{v}}_{\mathsf{max}} = 2^l - 1\}$, such that such wrap-around never occurs undetected.

We note that $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$ in itself affords a fully decentralized layer 2 confidential token transfer solution, since it is independent of the MPC servers. Thus allowing client's to send a receive confidential tokens in a peer-to-peer manner. This is needed to prevent leakage of exchange orders after-the-fact by analysing client's non-confidential tokens given as input and withdrawn as output from a privacy preserving smart contract execution. By allowing the privacy preserving smart contract executions to integrate in a greater payment ecosystem reasonably ensures that it is possible to hide token inputs and outputs from a privacy preserving smart contract execution by using them for confidential payment, similar to other confidential token systems.

We present a protocol $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$ which GUC-realizes $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ in Appendix C.1, where we also prove the following statement:

Theorem 1. *Protocol $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$ GUC-realizes functionality $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ in the $\mathcal{F}_{\mathsf{Clock}}$, $\mathcal{F}_{\mathsf{Ledger}}$, $\mathcal{F}_{\mathsf{NIZK}}$, $\mathcal{F}_{\mathsf{Setup}}$, $\mathcal{F}_{\mathsf{Sig}}$-hybrid model against any PPT-adversary corrupting any minority of committee $\mathcal{Q}$.*

3 Confidential contracts

We present our formal model of confidential contracts. We assume m clients $\{C_1, \ldots, C_m\}$ and servers $\{P_1, \ldots, P_n\}$ that interact with $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$, which extends $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$. For simplicity of presentation, we first present a single-round confidential contract functionality in Figure 2, and subsequently illustrate how it is easily extended to a multi-round contract functionality where clients can selectively choose to participate in specific rounds.

The choice of modelling $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$ as an extension of $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ arises from the relation between underlying protocols: confidential coins in $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$ that are committed to a confidential contract evaluation must be *locked* and subsequently *replaced* by a new set of output coins reflecting a new distribution of balances, determined by $\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}$. However, this requires verification operations over the homomorphic *commitment* representation of coins in $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$, which are not exposed by $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$.

We provide a brief sketch of the interface exposed by $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$. Upon initialization with an arithmetic circuit g encoding only the contract logic, users can enroll, specifying input string x and a confidential coin to input, identified by its id. Upon a completed *Enroll*, the functionality is prompted by servers to evaluate circuit g on both client input strings, interpreted as numerical values, and input balances, with checks to ensure g does not mint tokens. $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ permits clients to withdraw anytime to retrieve the private output string and output balance. $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$ permits the simulator to abort and indicate cheating servers, which are then penalized by the functionality.

Model of confidential contracts. Unlike public smart contracts deployed to $\mathcal{F}_{\mathsf{Ledger}}$, an instance of $\mathcal{F}_{\mathsf{Ident}}$ permits the computation of any arithmetic circuit on both private and public inputs. We model a confidential contract as an arithmetic circuit over a field $\mathbb{F}_p$ consistent with the domain that $\mathcal{F}_{\mathsf{Ident}}$ is realized with. A well-formed confidential contract permits the writing of both *numerical* and *financial* inputs from each client to its input gates. Further, we enforce a maximum circuit depth d_T prior to the circuit evaluation to bound the rounds of interaction in the MPC instance.

$$\big(([\,y_1\,],[\,\bar{\mathbf{w}}_1\,]),...,([\,y_m\,],[\,\bar{\mathbf{w}}_m\,])\big) \leftarrow \mathsf{eval}_g\big(([\,x_1\,],[\,\bar{\mathbf{v}}_1\,])....,([\,x_m\,],[\,\bar{\mathbf{v}}_m\,])\big)$$

Upon confidential evaluation of a contract circuit g with well-formed depth and gates, the following assertion must be performed at each run-time over confidential inputs and outputs of evaluated g: namely, that token supplies have been preserved.

$$\sum_{i\in[m]} [\,\bar{\mathbf{v}}_i\,] =^{?} \sum_{i\in[m]} [\,\bar{\mathbf{w}}_i\,] \tag{2}$$

One-round client-server interaction. Upon providing inputs to a confidential contract execution, clients can go off-line and retrieve confidential outputs with *Withdraw* at any later point in time.

Functionality $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$, extends $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$

$\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$ interacts with clients $\mathcal{C} = \{C_1, ..., C_m\}$ and servers $\mathcal{P} = \{P_1, ..., P_n\}$. The functionality exposes interfaces and and accesses the state of $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$. It is parameterized with max. circuit depth d_T, and collateral balance $\bar{\mathbf{v}}_{\mathsf{coll}}$.

Init: On (INIT, *sid*, g) from $P_i \in \mathcal{P}$ forward messages to $\mathcal{S}$. If $\mathcal{S}$ continues.
1. Run **GenAcct** and **Init** procedures on $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$.
2. Assert that g is a circuit and that $\mathsf{depth}(g) \leq d_T$, store g.
3. Assert $\mathsf{vk} \in \mathcal{K}[P_i]$ and $\mathcal{L}[\mathsf{vk}] \geq \bar{\mathbf{v}}_{\mathsf{coll}}$.
4. Set $\mathcal{L}[\mathsf{vk}] \leftarrow \mathcal{L}[\mathsf{vk}] - \bar{\mathbf{v}}_{\mathsf{coll}}$.
   - If all servers have successfully called **Init**, set state to `enroll`, tick $\mathcal{F}_{\mathsf{Clock}}$.

Enroll: Upon input (ENROLL, *sid*, x, id, vk) from client $C_j \in \mathcal{C}$,
1. Assert $\mathsf{vk} \in \mathcal{K}[C_j]$ and $\langle \mathsf{id}, \bar{\mathbf{v}} \rangle \in \mathcal{L}[\mathsf{vk}]$.
2. Forward (ENROLL, *sid*, id, vk) to $\mathcal{S}$, if $\mathcal{S}$ aborts, run **Abort**. Otherwise, continue.
3. Assert state is in `enroll` and $\exists \langle \mathsf{id}, \bar{\mathbf{v}} \rangle \in \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}]$: then remove $\langle \mathsf{id}, \bar{\mathbf{v}} \rangle$.
4. Store input $(x_j, \bar{\mathbf{v}}_j)$.
   - If all clients have successfully called **Enroll**, tick $\mathcal{F}_{\mathsf{Clock}}$.

Execute: Upon input (EXECUTE, *sid*) from $P_i \in \mathcal{P}$,
1. If EXECUTE received from all $\mathcal{P}$ and $\mathcal{F}_{\mathsf{Clock}}$ ticked since state update to `enroll`, forward (EXECUTE, *sid*) to $\mathcal{S}$ and wait for *Ok* or *Abort*. If *Ok*, continue.
   a. Evaluate circuit g over current user inputs $\{(x_j, \bar{\mathbf{v}}_j)\}_{j \in [m]}$ and client state.
   c. Store client states $\{(y_j, \bar{\mathbf{w}}_j)\}_{j \in [m]}$ read from output gates of g.
      - Assert $\sum_{j \in [m]} \bar{\mathbf{v}}_j = \sum_{j \in [m]} \bar{\mathbf{w}}_j$. Tick $\mathcal{F}_{\mathsf{Clock}}$.
2. Forward (EVALUATE, *sid*) to $\mathcal{S}$ and wait for *Ok* or *Abort*.
   - If *Ok* returned, set state to `evaluated` and tick $\mathcal{F}_{\mathsf{Clock}}$.
3. Send (OUTPUT, *sid*, $\{y_j, \bar{\mathbf{w}}_j\}_{j \in [m]}$) to $\mathcal{S}$ and wait for *Ok* or *Abort*.
   - If $\mathcal{S}$ aborts, it provides cheating server set $\mathcal{J}$, run **Abort** with $\mathcal{J}$.
4. For $j \in [m]$, get a unique id'_j from $\mathcal{S}$, and set $\mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}_j] \leftarrow \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}_j] \cup \{\langle \mathsf{id}'_j, \bar{\mathbf{w}}_j \rangle\}$.
5. Set state to `enroll` and tick $\mathcal{F}_{\mathsf{Clock}}$.

Withdraw: Upon (WITHDRAW, *sid*) from $C_j \in \mathcal{C}$, obtain newly stored outputs since last *Withdraw* by $C_j \in \mathcal{C}$. Return $((y_{j,1}, \langle \mathsf{id}'_{j,1}, \bar{\mathbf{w}}_{j,1} \rangle), ..., (y_{j,l}, \langle \mathsf{id}'_{j,l}, \bar{\mathbf{w}}_{j,l} \rangle))$.

Abort: Tick $\mathcal{F}_{\mathsf{Clock}}$,
a. If state is `enroll`, return server and client funds: update $\mathcal{L}$, $\mathcal{L}_{\mathsf{Conf}}$.
b. Else if state in `evaluated`, obtain cheating servers $\mathcal{J}$ from $\mathcal{S}$:
   - If $\mathcal{J} \neq \emptyset$, reimburse clients $\mathcal{C}$ and honest servers $\mathcal{P} \backslash \mathcal{J}$, then distribute $\mathcal{J}$'s collateral amongst $\mathcal{C}$: update $\mathcal{L}$, $\mathcal{L}_{\mathsf{Conf}}$ accordingly.
   - Else if $\mathcal{J} = \emptyset$, obtain $\{(y_j, \bar{\mathbf{v}}_j)\}_{j \in [m]}$ from last evaluation of circuit g.
     - For $C_j \in \mathcal{C}'$, sample $\mathsf{id}_j \leftarrow\!\!\$\ \mathbb{F}$ and set $\mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}_j] \leftarrow \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}_j] \cup \{\langle \mathsf{id}_j, \bar{\mathbf{v}}_j \rangle\}$.
     - Return collateral for all $\mathcal{P}$: update $\mathcal{L}$ accordingly.
c. Terminate.

Fig. 2: Functionality for Confidential Contracts

Collateral. Our need for collateral follows the same logic as in Insured MPC [9]. The collateral contract incentivizes the servers to continue to participate in the privacy preserving smart contract computation, and behave honestly as they would otherwise suffer a financial loss. While the underlying maliciously secure

MPC system will ensure that a server acting maliciously will cause an abort except with negligible probability, such an abort the adversary might have learned the output of the computation. This can in some situations have high value. Thus we require each server to give as collateral, strictly *more* than the maximum value they could gain from learning the output of a privacy preserving computation.

3.1 Realizing the confidential contract functionality

Overview of Protocol. Having provided a high-level overview of the protocol phase in Section 1, we now proceed to detail the individual protocol phases for the single-round privacy preserving smart contract execution and refer to Appendix C.2 for the full protocol description and UC-security proof, and to Sec. 3.2 for an outline of the multi-round protocol.

In Section 3.2 we extend the protocol (1) to realize multi-round, reactive confidential contracts and (2) to prevent minting of tokens in the case of full-server corruption.

Setup of contracts. Servers deploy instances of $\mathcal{X}_{\mathsf{Lock}}[\mathcal{X}_{\subseteq\mathsf{CLedger}}]$, $\mathcal{X}_{\mathsf{Collateral}}$ on $\mathcal{F}_{\mathsf{Ledger}}$. Since wrapper $\mathcal{X}_{\mathsf{Lock}}$ extends $\mathcal{X}_{\subseteq\mathsf{CLedger}}$, both are deployed and initialized as a single contract instance on $\mathcal{F}_{\mathsf{Ledger}}$ with shared contract id ($\mathsf{cn}_{\mathsf{Lock}}$) and shared state such as the confidential ledger ($\mathcal{L}_{\mathsf{Conf}}$). Here, the function of $\mathcal{X}_{\mathsf{Lock}}$ is to lock the confidential coins of clients input to the confidential contract evaluation, and to *replace* these with a new confidential distribution according to result of the contract evaluation. Further, $\mathcal{X}_{\mathsf{Lock}}$ is initialized with a threshold signature verification key $\mathsf{vk}_{\mathsf{TSig}}$, jointly generated by all servers via $\mathcal{F}_{\mathsf{TSig}}$: whenever servers agree on a new status of the contract evaluation in $\mathcal{F}_{\mathsf{Ident}}$, this agreement can be settled in $\mathcal{X}_{\mathsf{Lock}}$ with a threshold signature jointly generated via global functionality $\mathcal{F}_{\mathsf{TSig}}$. $\mathcal{X}_{\mathsf{Collateral}}$ is parameterized by $\mathsf{cn}_{\mathsf{Lock}}$ and is activated each time $\mathcal{F}_{\mathsf{Clock}}$ progresses: it obtains collateral from all participating servers. It observes any recorded cheating servers $\mathcal{J}$ stored in the state of contract instance $\mathsf{cn}_{\mathsf{Lock}}$ and enforces penalties accordingly.

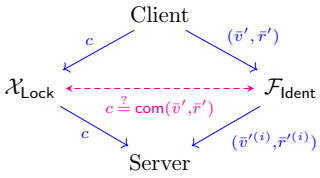
Client enrollment. Clients interact with $\mathcal{X}_{\mathsf{Lock}}$ to enroll a confidential coin it controls to the contract evaluation, and send both the coin commitment opening and numerical input x to an instance of $\mathcal{F}_{\mathsf{Ident}}$. Enrolled coins are removed from the confidential ledger $\mathcal{L}_{\mathsf{Conf}}$ maintained by $\mathcal{X}^{\subseteq\mathsf{CLedger}}$ and moved to a dedicated ledger $\mathcal{L}_{\mathsf{Lock}}$ for funds committed to a pending MPC computation in $\mathcal{F}_{\mathsf{Ident}}$.

Clients must also commit to a *output mask* during enrollment, which enables the subsequent redistribution of confidential coins without client interaction in the output phase of the contract evaluation. Here each client with confidential coin input c and numerical input x performs the following:

- Samples $\hat{y} \leftarrow\!\$\ \mathbb{F}$ as a numerical output mask and sends to $\mathcal{F}_{\mathsf{Ident}}$.
- Samples $\hat{\mathbf{w}} \leftarrow\!\$\ \mathbb{F}^{|\mathbb{T}|}$, $\hat{s} \leftarrow\!\$\ \mathbb{F}$, and computes mask commitment $\hat{c} \leftarrow \mathsf{com}(\hat{\mathbf{w}}, \hat{s})$.
- Sends mask commitment $\hat{c}$ to $\mathcal{X}_{\mathsf{Lock}}$ on $\mathcal{F}_{\mathsf{Ledger}}$.
- Sends mask commitment openings $(\hat{\mathbf{w}}, \hat{s})$ of $\hat{c}$ to $\mathcal{F}_{\mathsf{Ident}}$.

Here clients can also give any auxiliary input, x, needed for the privacy preserving smart contract computation.

Input verification. Upon enrollment of clients, servers must verify that the confidential coin c and mask commitment $\hat{c}$ sent to $\mathcal{X}_{\mathsf{Lock}}$ are consistent with their respective openings $(\bar{\mathbf{v}}, \bar{r})$ and $(\hat{\mathbf{v}}, \hat{r})$ sent to $\mathcal{F}_{\mathsf{Ident}}$ during enrollment. For simplicity of presentation, we illustrate the batched input verification of input confidential coins and their openings assuming a token universe size of $|\mathbb{T}| = 1$, such that $c = g^{\bar{v}} h^{\bar{r}}$. Input verification for output masks $\hat{c}$ and their openings submitted to $\mathcal{F}_{\mathsf{Ident}}$ follow similarly.



Each server obtains both confidential coin c from $\mathcal{X}_{\mathsf{Lock}}$ and *additive shares* of submitted openings thereof from $\mathcal{F}_{\mathsf{Ident}}$, namely $(\bar{v}'^{(i)}, \bar{r}'^{(i)})$. We write $\bar{v}'^{(i)} = (\bar{v} + \epsilon)^{(i)}$ and similarly for $\bar{r}'^{(i)}$, where the ϵ denotes the error or discrepancy that the adversary can introduce to $\bar{v}$. We employ a standard technique of evaluating a random linear combination over client inputs to verify consistency.

1. Servers jointly sample $\gamma, \alpha, \beta \leftarrow\!\!\$\ \mathbb{F}$ and open γ.
2. Each server locally computes the following on the inputs from m clients.
   - $\bar{v}'^{(i)}_{\mathsf{lin}} = \alpha^{(i)} + \gamma\, \bar{v}'^{(i)}_1 + \ldots + \gamma^m\, \bar{v}'^{(i)}_m$ and $r'^{(i)}_{\mathsf{lin}} = \beta^{(i)} + \gamma\, r'^{(i)}_1 + \ldots + \gamma^m\, r'^{(i)}_m$
   - Subsequently, it sends $\bar{v}'^{(i)}_{\mathsf{lin}}$ and $\bar{v}'^{(i)}_{\mathsf{lin}}$ to all other servers.
3. Each server locally reconstructs $\bar{v}'_{\mathsf{lin}} = \prod_{i \in [n]} \bar{v}'^{(i)}_{\mathsf{lin}}$ and $r'_{\mathsf{lin}} = \prod_{i \in [n]} r'^{(i)}_{\mathsf{lin}}$
4. Servers locally verify: $\prod_{i \in [n]} g^{\alpha^{(i)}} h^{\beta^{(i)}} \prod_{j \in [m]} c_j^{\gamma^j} \stackrel{?}{=} g^{\bar{v}'_{\mathsf{lin}}} h^{r'_{\mathsf{lin}}}$

Note that $\bar{v}'^{(i)}_{\mathsf{lin}}$ and $r'^{(i)}_{\mathsf{lin}}$ are shares held by servers and do not reveal the values of user inputs. We write $\bar{v}'_{\mathsf{lin}} = \alpha + \gamma\,(\bar{v}_1 + \epsilon_{\bar{v}_1}) + \ldots + \gamma^m\,(\bar{v}_m + \epsilon_{\bar{v}_m})$ and similarly for r'_{lin} to expose ϵ's introduced by the adversary. If ϵ values are committed to by the adversary before α, β, γ are sampled, we can interpret $\bar{v}'_{\mathsf{lin}} - \bar{v}_{\mathsf{lin}} = 0$ and $r'_{\mathsf{lin}} - r_{\mathsf{lin}} = 0$ as m - degree polynomials with coefficients chosen by the adversary that are later evaluated at some random coordinate γ: since verification step (4) implies exactly these assertions, the probability for an undetected non-zero error is therefore $m/|\mathbb{G}|$, where m is the number of polynomial roots, by the Schwartz-Zippel Lemma.

Execute. Servers call the **Evaluate** interface on $\mathcal{F}_{\mathsf{Ident}}$ to evaluate circuit g with input gates set to client inputs.

$$([x_1], [\hat{y}_1], [\bar{\mathbf{v}}_1], [r_1], [\hat{\mathbf{w}}_1], [\hat{s}_1]), \ldots, ([x_m], [\hat{y}_m], [\bar{\mathbf{v}}_m], [r_m], [\hat{\mathbf{w}}_m], [\hat{s}_m])$$

Upon secure evaluation, outputs in form of numerical values and balances are written to the output gates of g: $\big(([y_1], [\bar{\mathbf{w}}_1]), \ldots, ([y_m], [\bar{\mathbf{w}}_m])\big)$. Before masking these for opening, the servers then perform a confidential consistency check to ensure the preservation of tokens as shown in Equation (2).

Masked output values are obtained by applying the masking values input by users, $[\,y'_j\,] = [\,y_j\,] + [\,\hat{y}_j\,]$ and similarly for balances, $[\,\bar{\mathbf{w}}'_j\,] = [\,\bar{\mathbf{w}}_j\,] + [\,\hat{\mathbf{w}}_j\,]$ and generating a joint signature $\sigma_{\mathsf{vk}_{\mathsf{TSig}}}(\mathsf{evaled})$ via $\mathcal{F}_{\mathsf{TSig}}$, that is sent to $\mathcal{X}_{\mathsf{Lock}}$ on $\mathcal{F}_{\mathsf{Ledger}}$. Upon verification, the $\mathcal{X}_{\mathsf{Lock}}$ contract updates the state of protocol execution, reflecting completion of the *Execute* phase.

Open. Servers run **Optimistic Reveal** in $\mathcal{F}_{\mathsf{Ident}}$ to open masked numerical outputs and balances $\big((y'_1, \bar{\mathbf{w}}'_1), ..., (y'_m, \bar{\mathbf{w}}'_m)\big)$. Should all servers agree on the successful completion of the contract evaluation, they jointly sign all *masked* outputs and send these to $\mathcal{X}_{\mathsf{Lock}}$ (on $\mathcal{F}_{\mathsf{Ledger}}$), which then computes the *unmasked* confidential coins for clients with the newly computed distribution as follows. Given the masked output balance $\bar{\mathbf{w}}'$ from $\mathcal{F}_{\mathsf{Ident}}$ and the coin mask $\hat{c}$ sampled by a client in **Enroll**, contract $\mathcal{X}_{\mathsf{Lock}}$ computes

(a) The masked confidential coin: $c^{\mathsf{out}\,\prime} \leftarrow \mathbf{g}^{\bar{\mathbf{w}}'} h^0$
(b) The unmasked confidential coin: $c^{\mathsf{out}} \leftarrow c^{\mathsf{out}\,\prime} \cdot \hat{c}^{-1}$

We rewrite (b) as $c^{\mathsf{out}} = \mathbf{g}^{\bar{\mathbf{w}}' - \hat{\mathbf{w}}} h^{-\hat{s}} = \mathsf{com}(\bar{\mathbf{w}}, -\hat{s})$ to expose the unmasking of the output coin without any knowledge of the final balance. $\mathcal{X}_{\mathsf{Lock}}$ subsequently stores unmasked output coin c^{out} in the confidential ledger in $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$, thereby settling the output balance distribution read from output gates of contract circuit g. Should $\mathcal{X}_{\mathsf{Lock}}$ successfully verify the signed outputs, $\mathcal{X}_{\mathsf{Collateral}}$ will infer from the state of $\mathcal{X}_{\mathsf{Lock}}$ the completion of a successful round and return the deposited collateral to the servers.

Withdraw. Upon a successful **Open**, the output of the confidential contract evaluation has completed. Each client can obtain their masked output $(y', \bar{\mathbf{w}}')$ from $\mathcal{X}_{\mathsf{Lock}}$ and newly minted c_{out} from $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ anytime following a successful execution of a contract evaluation. Let $\hat{y}$ and $(\hat{\mathbf{w}}, \hat{s})$ be the output masks generated by the client in **Enroll**. The withdrawing client obtains

(a) The numerical output: $y \leftarrow y' - \hat{y}$
(b) The opening of the output coin: $(\bar{\mathbf{w}}, s) \leftarrow (\bar{\mathbf{w}}' - \hat{\mathbf{w}}, -\hat{s})$

Thus, their the tokens are still confidential and that clients can transfer or redeem these using $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$ in Fig. 10.

Abort. If the protocol aborts prior to the completion of the **Execute** phase, client funds are simply returned by $\mathcal{X}_{\mathsf{Lock}}$ and collateral deposited to $\mathcal{X}_{\mathsf{Collateral}}$ is returned. If servers have agreed upon the completion of **Execute**, honest servers can interact with $\mathcal{F}_{\mathsf{Ident}}$ to either (a) obtain shares that are verifiable and enable reconstruction of the output or (b) identify cheating servers (Figure 7). Thus, $\mathcal{X}_{\mathsf{Lock}}$ as a registered public verifier, can identify cheating servers by either verifying shares with $\mathcal{F}_{\mathsf{Ident}}$, or obtaining the identities of servers $\mathcal{J}$ that refuse to participate in revealing their shares and allowing their verification. Cheating servers lose their collateral held by $\mathcal{X}_{\mathsf{Collateral}}$ which is redistributed to clients.

We present the full protocol $\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}$ which GUC-realizes $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$ in Appendix C.2 and prove the following statement.

Theorem 2. *$\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}[\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}]$ realizes $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}[\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}]$ in the $\mathcal{F}_{\mathsf{Clock}}$, $\mathcal{F}_{\mathsf{Ident}}$, $\mathcal{F}_{\mathsf{Ledger}}$, $\mathcal{F}_{\mathsf{NIZK}}$, $\mathcal{F}_{\mathsf{Setup}}$, $\mathcal{F}_{\mathsf{Sig}}$, $\mathcal{F}_{\mathsf{TSig}}$-hybrid model against any PPT-adversary corrupting at most $n-1$ of the n servers $\mathcal{P}$ statically and any minority of $\mathcal{Q}$.*

3.2 Extensions of the confidential contract protocol

We extend the $\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}$ in this section to support multi-round confidential contracts and to prevent servers from arbitrarily minting tokens in $\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}[\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}]$ in the case of *full* server corruption, enabling security degradation to leave the supply of the underlying confidential ledger in tact, albeit with an additional cost in MPC operations requiring communication and data posted to the underlying ledger (Table 2).

Multi-round confidential contracts. We now demonstrate how our default model of confidential contracts, shown in previous sections, can be extended to a multi-round model, where clients can provide fresh inputs and obtain continuous outputs in a long-running confidential blockchain application.

This is facilitated by our model of confidential contracts, which does not require server-client interaction beyond the *Open* phase, along with the reactive interface of our MPC functionality (Appendix A.1), which permits the selective opening of secrets and indefinite number of circuit evaluations on stored secret values. This allows the set of MPC servers to keep an internal secret shared state, off-chain. Furthermore, since we use *outsourced* MPC [44] and rely on a reactive MPC scheme, any multi-round computation can simply be considered a single *reactive* computation, with interleaved input and output. In fact, clients at most hold a state dependent on their own input and expected outputs through out execution of MPC. Thus whatever confidential state is needed, the MPC servers will simply store this secretly, and collectively, throughout the multiple computations of the private smart contracts with different clients giving input and receiving output.

Consider one confidential contract execution and let, without loss of generality, the confidential state of a client be a tuple consisting of a numerical value and balance: $[\,s_j\,] = ([\,y_i\,], [\,\bar{\mathbf{w}}_i\,])$. Further, let the *confidential contract state* be defined over all confidential client states $\mathsf{st} = ([s_1], ..., [s_m])$, which is stored from the previous contract evaluation round or given as the initial confidential contract state. We define a *confidential contract state transition* that consumes a fresh set of confidential contract inputs $\mathsf{st}^{\mathsf{in}} = ([s_1^{\mathsf{in}}], ..., [s_m^{\mathsf{in}}]) = (([\,x_1^{\mathsf{in}}\,], [\,\bar{\mathbf{v}}_1^{\mathsf{in}}\,]), ..., ([\,x_m^{\mathsf{in}}\,], [\,\bar{\mathbf{v}}_m^{\mathsf{in}}\,]))$, such that the the *current contract circuit* $\mathbf{g}$ is evaluated over both st and $\mathsf{st}^{\mathsf{in}}$ to obtain a new confidential state st' and an encoding of the updated circuit $\mathbf{g}'$ to be evaluated in the next round.

$$\big([\,\mathbf{g}'\,], [\,s_1'\,], ..., [\,s_m'\,]\big) \leftarrow \mathsf{eval}_{\mathbf{g}}\big([s_1^{\mathsf{in}}], ..., [s_m^{\mathsf{in}}], [\,s_1\,], ..., [\,s_m\,]\big)$$

Upon successful completion of a round evaluation, circuit $\mathbf{g}'$ will be securely opened, stored and evaluated by the servers in the following round. Each client can retrieve its new state by executing *Withdraw*.

However, the set of clients wishing to give input to a confidential contract evaluation might not always be the same. Thus we now argue a simple extension to our $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$ model to permit clients can selectively participate in the **Enroll** phase of a round, or to *skip* a given round by ticking the $\mathcal{F}_{\mathsf{Clock}}$ after calling a **Skip Round** interface.

We propose an output budget for each client corresponding to the number of *unused*, pre-processed output masks: in each round, a client will receive a masked output which can be retrieved from the contract $\mathcal{X}_{\mathsf{Lock}}$ on $\mathcal{F}_{\mathsf{Ledger}}$, regardless whether it provides a new input and participates in **Enroll**: masked outputs for a specific client are generated in each round until its pre-processed output masks have been consumed. The evaluation of the confidential contract in each round is still evaluated over *all clients* and their secret state $\mathsf{st} = ([s_1], ..., [s_m])$, even if only a subset have provided fresh inputs for a round. A client **Skip** implies evaluating the contract circuit over default input values.

Each participation in an **Enroll** phase of a round permits a client to *restore* its depleted output budget, by generating masks in commitment form and inputting their openings to the MPC instance, which are subsequently verified for consistency in the **Verify Input** protocol phase. Each output mask can be associated with a *fee* paid to the servers executing the MPC: once all output budgets (and associated output masks) are consumed, the multi-round confidential contract can terminate safely.

We observe, that this approach also implies that the expensive **Init** phase only needs to be carried out once, assuming the set of MPC servers don't change and no server actively cheats (i.e. causes the execution of the *abort* phase to an extend where a malicious server is identified at the smart contract level). Thus, servers only need to setup threshold keys, smart contracts and collateral once, but naturally need to reevaluate this setup in case a server is confirmed to cheat and penalized.

Mitigation of token minting. Under full server corruption, it is possible for the adversary to mint confidential balances beyond the supply of underlying tokens wrapped by $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$. This is because in our default protocol $\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}$ shown in Figure 12, any output coin distribution accompanied by a verifying threshold signature (via $\mathcal{F}_{\mathsf{TSig}}$) will be accepted by $\mathcal{X}_{\mathsf{Lock}}$; no coin sum-checks or range-proofs enforce the preservation of confidential token supplies (See Equation 1). This is not publicly detectable, even if $\mathcal{X}_{\mathsf{Lock}}$ implemented a product consistency check over input and output coins with correlated commitment randomness, $\prod_{j\in[m]} c_j = \prod_{j\in[m]} c_j^{\mathsf{out}}$, as hidden balances can exceed $\bar{\mathbf{v}}_{\mathsf{max}} = 2^l - 1$, and p additional units of each token type can be minted.

There are several ways in which this can be mitigated. If we accept client interaction during the output phase, then the client can simply retrieve their output commitments as part of the protocol and subsequently generate range-proofs and a zero-sum proof over input and output coins and post this to the smart contract $\mathcal{X}_{\mathsf{Lock}}$. The smart contract can then validate these proofs and thus ensure that no tokens have been minted or destroyed as part of the private smart contract execution. Unfortunately, this also allows a single malicious client

to abort the execution after observing its own outputs *and* goes against our goal of minimizing client interaction; in contrast to our standalone protocol $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$ (Figure 13), clients would be required to be online in the **Open** phase. Instead we suggest an approach based on bit-decomposition of token amounts, along with the masks. Based on the decomposition, the zero-sum property of input and output coin commitments (Equation 1) is ensured by a proof to $\mathcal{X}_{\mathsf{Lock}}$, constructed by the servers *without* the need for computing cryptographic primitives inside the MPC circuit.

More concretely, in the following we show an extension of $\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}$ that prevents the minting of tokens under full server corruption, at the cost of a constant-factor increase in communication complexity. This is based on the bit decomposition approach as in Banerjee *et al.* [6], but greatly improves on the protocol efficiency by *not* requiring any NIZK's and commitments to be generated inside the MPC circuit.

Let l be the number of bits such that each coin balance does not exceed $\bar{v}_{\mathsf{max}} \leq 2^l - 1$. In the **Enroll** phase, clients each generate bit a commitment pair $(c_0 = \mathsf{com}(b_0, s_0), c_1 = \mathsf{com}(b_1, s_1))$ for each bit position $k \in [l]$, such that $b_i = 0 \wedge b_{i-1} = 1$ for random $i \leftarrow\!\!\$\ \{0,1\}$. Let π denote the bit permutation sampled by the client for the bit position $k \in [l]$, such that:

$$\pi(k) = \begin{cases} 0 & b_{k,0} = 0 \wedge b_{k,1} = 1 \\ 1 & b_{k,0} = 1 \wedge b_{k,1} = 0 \end{cases}$$

This permutation on the individual bits is later used to mask the bit-decomposed output. Commitment pairs are posted to $\mathcal{F}_{\mathsf{Ledger}}$, together with an efficient sigma proof that commitments are to bit values [42], incurring an additional communication complexity logarithmic in the size of the commitment group order.

During the **Enroll** phase, users input the opening to these bit commitment pair in the permuted order:

$$([\,\bar{v}\,], [\,\bar{r}\,], \{([\,b_{0,k}\,], [\,s_{0,k}\,], [\,b_{1,k}\,], [\,s_{1,k}\,])\}_{k\in[l]})$$

where $c_{\mathsf{in}} = (\bar{v}, \bar{r})$ is the opening to the confidential input coin, and each tuple $(b_{0,k}, s_{0,k}, b_{1,k}, s_{1,k})$ is the opening to the k'th bit commitment pair with permuted bit ordering. We adopt a well-formedness check on bits input to $\mathcal{F}_{\mathsf{Ident}}$ from [40]: servers assert for each $k \in [l]$ bit position, that one of $[\,b_{k,0}\,], [\,b_{k,1}\,]$ holds the value 1 and the other holds the value 0. Concretely, for bit pair $([\,b_0\,], [\,b_1\,])$, servers jointly sample and open $\alpha, \beta, \gamma, \leftarrow\!\!\$\ \mathbb{F}$, and compute:

$$[\,t\,] = \alpha \cdot ([\,b_0\,] \cdot [\,b_0\,] - [\,b_0\,]) + \beta \cdot ([\,b_1\,] \cdot [\,b_1\,] - [\,b_1\,]) + \gamma \cdot ([\,b_0\,] \cdot [\,b_1\,])$$

$$[\,t'\,] = ([\,b_0\,] + [\,b_1\,])$$

Upon securely opening t and t', servers assert that $t = 0 \wedge t' = 1$. Consistency between all commitments and their openings input to $\mathcal{F}_{\mathsf{Ident}}$ are verified during **Verify input** phase by the servers.

Importantly, the financial output of a client is output in bit-decomposed form, where individual bits are permuted in the ordering as chosen by the clients.

$$(b'_1, ..., b'_l)$$

Let $(b_1, ..., b_l)$ denote the true bit-decomposition of a clients output balance. Then $b'_k = b_k$ if $\pi(k) = 0$ and is bit permuted otherwise, where π denotes the permutation chosen by the client in the enroll phase.

For contract $\mathcal{X}_{\mathsf{Lock}}$ to generate the client output coin from bit commitments submitted during **Enroll**, it computes.

$$c_{\mathsf{out}} = \prod_{k \in [l]} c_{k,i}^{2^k} \text{ where } i = b'_k \in \{0, 1\}$$

Here, note that b'_k is interpreted as selector for bit commitment pair $(c_{k,0}, c_{k,1})$ for bit position k. As both $b'_k = i$ and the bit message of $c_{k,i}$ are permuted by $\pi(k)$, the hidden balance of c_{out} is unmasked. Given the generation of output coins from l bit balance representations, confidential output balances are bounded by $2^l - 1 = \bar{v}_{\mathsf{max}}$.

It remains to prove consistency between input and output commitments to $\mathcal{X}_{\mathsf{Lock}}$ to ensure no token minting occurred. For this, servers compute the commitment randomness for each client output coin and the difference in commitment randomness between the input and output coins.

$$[\, s_{\mathsf{out}} \,] = \sum_{k \in [l]} 2^k \cdot [\, s_{k,i} \,] \text{ where } i = b'_k \in \{0, 1\} \qquad [\, \bar{r}_{\mathsf{diff}} \,] = \sum_{j \in [m]} [\, \bar{r}_{\mathsf{in},j} \,] - [\, s_{\mathsf{out},j} \,]$$

Servers locally compute $h^{\bar{r}^{(i)}_{\mathsf{diff}}}$ over the local share value of $[\, \bar{r}_{\mathsf{diff}} \,]$ and send it to all other servers. Each server then reconstructs $h^{\bar{r}_{\mathsf{diff}}}$ and verifies that sum of confidential input and output balances must be equal and that no tokens are minted (balance over-flow is mitigated by bounding output balances by $2^l - 1$).

$$\prod_{j \in [m]} c_{\mathsf{in},j} = h^{\bar{r}_{\mathsf{diff}}} \cdot \prod_{j \in [m]} c_{\mathsf{out},j}$$

We outline the overhead of this approach to prevent malicious minting when all servers are corrupted in Tab. 2, when assuming that Schnorr proofs are added for each commitment to allow extraction (though not in UC) and when using the work of Reistad and Toft [69] to do the needed bit decomposition in MPC.

4 Efficiency

In this section, we estimate the efficiency of our solution. We note that since previous works focus on using zero knowledge proofs and a trusted contract manager, we refrain from directly comparing our efficiency to their works. The

Table 2: Complexity of the per user overhead by using the stand-alone token minting mitigation approach.

	Exponentiation	MPC mult.
User	$6 \cdot l$	0
Server	$8 \cdot l + 1$	$42.5 \cdot l + 15$
Comm. $\#\mathbb{G}$ elem.	$O(n \cdot l)$	$O(n^2 \cdot l)$

closest previous works to ours is the Hawk family [54, 6, 7]. Unfortunately neither of the works provide an efficiency analysis, making it hard to provide a meaningful comparison. However, we note they all require computation of cryptographic primitives (commitments and ZKPs) in MPC. Thus requiring strictly more MPC computation, *along* with a larger (and hence) slower field of computation, as this field is needed to facilitate *computational* security of the cryptographic primitives they compute in MPC. In the following analysis, we assume Bulletproofs for range proofs and standard Fiat-Shamir Schnorr proofs of knowledge of exponents using elliptic curves. Although neither of these are UC-secure since knowledge extraction requires rewinding, there is evidence [41] that these techniques can be made non-malleable in the algebraic group model. Hence, for the purpose of efficiency we believe it is reasonable to forgo the formal UC security in this section. We use BLS threshold signatures and for simplicity we assume the size of the group used for BLS and commitments is the same, although it will in practice be slightly larger for BLS.

		Init	Execution	Abort
User	**exp**	2	2	0
Server	**exp**	$2 + 2(n-1)$	$6\|\mathcal{C}\| + 2$	0
	pair	0	$n - 1$	0
	mult	0	$z\|\mathcal{C}\|$	0
SC comp.	**exp**	0	$2\|\mathcal{C}\|z$	$\|\mathcal{C}\|$
	pair	0	2	0
SC call space	$\#\mathbb{G}$ elem.	3	$\|\mathcal{C}\|z$	$O(n\|\mathcal{C}\|z)$
Comm.	$\#\mathbb{G}$ elem.	$O(n)$	$O(n^2 \cdot z \cdot \|\mathcal{C}\|)$	$O(n^2 \cdot z \cdot \|\mathcal{C}\|)$

Table 3: Complexity of our protocol when executing one $\underline{\mathsf{C}}\mathsf{Contract}$, *excluding* the computation of contract circuit g in MPC. We assume $|\mathcal{C}|z > s$ for statistical security parameter s, where z is the amount of input/output for each client in the set of clients $\mathcal{C}$, including the hidden token amount. $n = |\mathcal{P}|$ is the amount of servers and **mult** denotes the number of multiplications in MPC.

We outline the amount of heavy computations needed for our core protocol in Table 3, *except* what is needed by the underlying MPC computation computing the contract circuit g, reflecting the privacy preserving smart contract $\underline{\mathsf{C}}\mathsf{Contract}$. Concretely we count the amount of group exponentiations when as-

suming that the Pedersen commitments are realized using elliptic curves, along with pairings assuming BLS [16] has been used for realizing distributed signatures. The table only contains the complexity of executing one instance of $\underline{\mathsf{C}}\mathsf{Contract}$, but we note that execution of multiple contracts is slightly sublinear in the complexity of a single execution. The *Abort* column illustrates the *additional* overhead associated with a cheating party.

	Mint	ConfTransfer	Redeem
User	4	$O(\log(\bar{v}_{\mathsf{max}}) \cdot \log(\log(\bar{v}_{\mathsf{max}})))$	3
SC comp.	3	$O(\log(\bar{v}_{\mathsf{max}}))$	3
SC space	3	$2\log(\bar{v}_{\mathsf{max}}) + 10$	4

Table 4: Complexity of $\underline{\mathsf{C}}\mathsf{Ledger}$ in group exponentiation and amount of group elements stored, when $\bar{v}_{\mathsf{max}}$ is the maximum amount of allowed tokens (Recall $|\mathcal{C}| \cdot \bar{v}_{\mathsf{max}} < |\mathbb{G}|$).

When it comes to our confidential token layer, we outline the complexity in Table 4. We note that the constant in the complexity of *Confidential Transfer* reflects two range proofs over $\log(|\mathbb{G}|/2)$, under the assumption that BulletProofs are used [19]. Although if the domain of the token amounts is further limited from $\mathbb{G}$ to $\bar{v}_{\mathsf{max}} < |\mathbb{G}|/|\mathcal{C}|$ then they can be reduced to range proofs of $[0; \bar{v}_{\mathsf{max}} - 1]$ and thus complexity $O(\bar{v}_{\mathsf{max}} \cdot \log(\bar{v}_{\mathsf{max}}))$.

In both tables the amount of smart contract space is only what needs to be submitted. The persistent space use needed is only $3+3|\mathcal{C}|$ group elements, if we assume that the storage used when posting to $\mathcal{X}_{\mathsf{Lock}}$ in *evaluate* and *open* gets overwritten the next time the servers call these methods.

The round complexity for all steps of both the confidential token layer protocols and our core protocol is constant, assuming g has constant multiplicative depth. Otherwise, the computation of g dominates the round complexity. Furthermore, we note that once the MPC servers have executed *Init* and the clients already hold hidden tokens, then an execution of $\mathsf{ConfContract}$, only requires three sequential calls to the underlying blockchain.

While we have not implemented our protocol we can approximate the expected runtime through the benchmark of group exponentiations, pairing operations, MPC multiplications along with network speeds and latency. Concretely if $\bar{\mathbf{v}}_{\mathsf{max}} = 2^{64}$ then a BulletProof range proof can be constructed in less than 7 ms and verification can be done in less than 2 ms [5] and less than 2 ms per curve multiplication, whereas a pairing can be done in less than 3 ms [6] on Intel i-series machines. For the MPC computation many schemes, such as SPDZ, supports an online/offline paradigm where the bulk of the computation needed to do a multiplication (an offline phase) can be computed before the function to compute, or input to compute on, is known. The offline phase is orders of magnitude slower

[5] Using the Dalek library with Ristretto255 [76].
[6] Using MIRACL with BN-128 [60].

than the only phase, which only require a additions and multiplications linear in the amount over server, over the field where the MPC computation happens. This can be used to significantly improve the overall latency of the protocol. For completeness we note that a multiplication triple can be generated in less than 0.05 ms when using Overdrive [49] for a 128 bit domain with 2 servers.

Based on these numbers we conclude that network latency will most likely be the bottleneck in practice. In particular this will be true if servers are located in different countries rather than in the same datacenter. As a quick ping will show, that even AWS in different countries in Europe can reach a latency of 30 ms. Thus even though the amount of rounds are constant, even a double digit amount of rounds can result in the protocol taking longer than a second.

Interesting complexity observations. The clients only need to execute *one* round of chain communication and a few rounds of server communication to give input to ConfContract. No matter how many iterations the client's input will be in use in ConfContract. The client only needs to read the chain to use the confidential tokens it end up receiving as output. In the cross-chain setting this can for example be used to continuously exchange a few tokens of one type with tokens of another type, thus avoiding large orders which could lead to market unrest. Because of this feature an exchange system using our protocol could limit the magnitude of an order but still allow large exchange at a given price by locking in an initial price, but carrying out the whole exchange in small increments of time.

Furthermore we note that the whole flow of the client is so lightweight that we expect it can be realized within the 1 second, which is the maximal amount of latency a user can be presented with without having their flow of through interrupted [63].

Comparison with P2DEX. Our protocol mainly differs from P2DEX since it allows computation on not just hidden auxiliary input but also hidden token amounts. The features allowing this is the use of our layer 2 confidential token smart contract, CLedger, which then requires commitments and proof-of-knowledge and range-proof on these. Furthermore, we require the linking of commitments to our MPC scheme. Most of this overhead is not needed in P2DEX. Concretely with our efficiency metric it only requires $m|\mathcal{C}|$ MPC multiplications, and $m|\mathcal{C}|$ threshold signatures with identifiable abort, of the type native of the underlying blockchain. However, most blockchains use ECDSA for which the most efficient scheme with identifiable abort [26] uses $10n$ exponentiation in an elliptic curve and $90n$ operations in a Paillier ring. As expected this becomes the main bottleneck in P2DEX. The reason we can avoid this overhead is through the use of a holding contract. This ensures that we only need to do a single distributed signature on *all* the transfers that need to be completed after a given round. In P2DEX, distributed signatures were needed for *each* transaction to *each* client, after the MPC computation. Although our holding smart contract idea has the minor disadvantage that Turing complete smart contracts need to be deployed on *each* chain we wish to have out system support. We should note

that the idea of using a holding smart contract could actually also be applied directly to P2DEX, as it is not contingent on working with hidden token amounts. Thus improving the efficiency of P2DEX significantly since BLS threshold signatures with identifiable abort follows trivially from the BLS construction which only requires a single pairing.

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A Extended preliminaries

A model of smart contracts. $\mathcal{F}_{\mathsf{Ledger}}$ parses authenticated messages which can authorize the deployment and activation of smart contracts, each modelled with a state transition function encoded as an arithmetic circuit T of maximum depth d_T, thereby enforcing a notion of bounded termination. Each contract maintains a public state fragment $\gamma \in \{0,1\}^*$ that is updated by circuit T upon the evaluation of each authenticated CallContract message. Each contract also maintains a balance $\bar{\mathbf{w}}$ of $\mathbb{T}$. We sketch the evaluation of a smart contract call with parameters $\mathsf{cn}, \mathsf{fn}, x, \bar{\mathbf{v}}$ authorized by signature verification key vk:

- *Contract identifier* cn selects the contract instance for evaluation.
- *Function selector* fn is an input that identifies the *contract interface* being evaluated, facilitating the logical separation of contract descriptions.
- *Input string* $x \in \{0,1\}^*$ denotes parameters input to circuit T: it is logically evaluated by the contract interface selected by fn.
- *Token balance* $\bar{\mathbf{v}}$ is provided to the contract call and is subtracted from the ledger entry associated with verification key vk.

The circuit T associated with contract instance cn is then evaluated on input $(\nu \,|\, \gamma \,|\, \bar{\mathbf{w}} \,|\, \mathsf{cn}, \mathsf{fn}, x, \bar{\mathbf{v}}, \mathsf{vk})$, where ν denotes $\mathcal{F}_{\mathsf{Clock}}$ round at the time of the call, and γ denotes the contract state stored by $\mathcal{F}_{\mathsf{Ledger}}$. Upon completed evaluation of T, $\mathcal{F}_{\mathsf{Ledger}}$ reads the encoding of a state transition $\mathcal{L}|\gamma|\bar{\mathbf{w}} \rightarrow^{\mathsf{ts}} \mathcal{L}'|\gamma'|\bar{\mathbf{w}}'$ from the output gates of evaluated T, thereby updating ledger, contract state and contract balance. Here, $\mathcal{F}_{\mathsf{Ledger}}$ asserts token supplies over $\mathbb{T}$ are preserved and that non-calling account balances cannot decrease from applying update ts.

We note the presence of call-back gates permitted in contract circuits deployed to $\mathcal{F}_{\mathsf{Ledger}}$, related to a UC-modelling technicality described in more detail in Appendix B.1. Concretely, these gates permit the UC functionality $\mathcal{F}_{\mathsf{Ledger}}$ to forward verification calls to hybrid functionalities $\mathcal{F}_{\mathsf{Ident}}$ and $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$ via an honest majority committee $\mathcal{Q}$. Thus, in the hybrid $\mathcal{F}_{\mathsf{Ident}}$, $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$-setting, the simulator maintains the ability to equivocate and efficiently extract inputs from dishonest parties.

Pedersen commitments. Let g, h denote random generators of $\mathbb{G}$ such that nobody knows the discrete logarithm of h base g, i.e., a value w such that $g^w = h$. The Pedersen commitment scheme [67] to an $s \in \mathbb{Z}_p$ is obtained by sampling $t \leftarrow\!\!\$\ \mathbb{Z}_p$ and computing $\mathsf{com}(s,t) = g^s h^t$. Hence, the commitment $\mathsf{com}(s,t)$ is a value uniformly distributed in $\mathbb{G}$ and opening the commitment requires to reveal the values of s and t. The Pedersen commitments are additively homomorphic, i.e., starting from the commitment to $s_1 \in \mathbb{Z}_p$ and $s_2 \in \mathbb{Z}_p$, it is possible to compute a commitment to $s_1 + s_2 \in \mathbb{Z}_p$, i.e., $\mathsf{com}(s_1,t_1) \circ \mathsf{com}(s_2,t_2) = \mathsf{com}(s+1+s_2, t_1+t_2)$.

(Global) Universal Composability. In this work, the (Global) Universal Composability or (G)UC framework [23, 25] is used to analyze security. Due to space constraints, we refer interested readers to the aforementioned works for more details. We generally use $\mathcal{F}$ to denote an ideal functionality and Π for a protocol. We implicitly assume private and authenticated channel between each pair of parties.

Several functionalities in this work allow public verifiability. Following Badertscher *et al.* [5] we dynamically allow the construction of a set of verifiers $\mathcal{V}$ through register and de-register commands. The adversary, $\mathcal{S}$ will always be allowed to obtain the list of registered verifiers. Concretely we implicitly assume all functionalities with public verifiability include the following interfaces (which are omitted in the concrete boxes for simplicity):

Register: Upon receiving (REGISTER, *sid*) from some verifier $\mathcal{V}_i$, set $\mathcal{V} \leftarrow \mathcal{V} \cup \mathcal{V}_i$ and return (REGISTERED, $sid, \mathcal{V}_i$) to $\mathcal{V}_i$.

Deregister: Upon receiving (Deregister,sid) from some verifier $\mathcal{V}_i$, set $\mathcal{V} = \mathcal{V} \setminus \mathcal{V}_i$ and return (DEREGISTERED, $sid, \mathcal{V}_i$) to $\mathcal{V}_i$.

Is Registered: Upon receiving (IS-REGISTERED, *sid*) from $\mathcal{V}_i$, return (IS-REGISTERED, sid, b) to $\mathcal{V}_i$, where $b = 1$ if $\mathcal{V}_i \in \mathcal{V}$ and $b = 0$ otherwise.

Get Registered: Upon receiving (GET-REGISTERED, *sid*) from the ideal adversary $\mathcal{S}$, the functionality returns (GET-REGISTERED, $sid, \mathcal{V}$) to $\mathcal{S}$. The above instructions can also be used by other functionalities to register as a verifier of a publicly verifiable functionality.

Global clock. As some parts of our work are inherently synchronous, we model rounds using a global clock functionality $\mathcal{F}_{\mathsf{Clock}}$ as in [5, 48, 52]. In Fig. 3 we show the global UC clock functionality, $\mathcal{F}_{\mathsf{Clock}}$, we need, taken verbatim from the work of Baum *et al.* [11]. We note that in the real execution all parties will send messages to, and receive them, from $\mathcal{F}_{\mathsf{Clock}}$. Whereas in the simulated case only the ideal functionality, other global functionalities as well as the corrupted parties will do so. Throughout this work, we will write "update $\mathcal{F}_{\mathsf{Clock}}$" as a short-hand for "send (UPDATE, *sid*) to $\mathcal{F}_{\mathsf{Clock}}$".

Functionality $\mathcal{F}_{\mathsf{Clock}}$

$\mathcal{F}_{\mathsf{Clock}}$ is parameterized by a variable ν, sets $\mathcal{P}$,$\mathcal{F}$ of parties and functionalities respectively. It keeps a Boolean variable d_J for each $J \in \mathcal{P} \cup \mathcal{F}$, a counter ν as well as an additional variable u. All d_J, ν and u are initialized as 0.

Clock update: Upon receiving a message (UPDATE) from $J \in \mathcal{P} \cup \mathcal{F}$:
1. Set $d_J = 1$.
2. If $d_F = 1$ for all $F \in \mathcal{F}$ and $d_P = 1$ for all honest $P \in \mathcal{P}$, then set $u \leftarrow 1$ if it is 0.

Clock read: Upon receiving a message (READ) from any entity:
1. If $u = 1$ then first send (TICK, *sid*) to $\mathcal{S}$. Next set $\nu \leftarrow \nu + 1$, reset d_J to 0 for all $J \in \mathcal{P} \cup \mathcal{F}$ and reset u to 0.
2. Answer the entity with (READ, ν).

Fig. 3: Global UC functionality $\mathcal{F}_{\mathsf{Clock}}$ for the clock.

Signatures. We will implicitly assume access to a global digital signature ideal functionality $\mathcal{F}_{\mathsf{Sig}}$ as defined in [24] (where it is also shown any EUF-CMA signature scheme realizes it), which is used for signing transactions to a ledger. We also use a global UC secure threshold signature scheme which offers identifiable abort. We denote this functionality $\mathcal{F}_{\mathsf{TSig}}$ and define it in Fig. 4 (which is taken verbatim from the work of Baum *et al.* [11]). The functionality allows a set of n parties to collaboratively sign a message m, and allows the adversary to corrupt up to $n - 1$ parties without being able to forge signatures. That is, we assume the full-threshold setting. Thus its behaviour matches that of

$\mathcal{F}_{\mathsf{Sig}}$, although it additionally allows $\mathcal{S}$ to choose the string of shares that later get combined into a signature. Although under the constraint that $\mathcal{S}$ has to choose both the signature shares and the actual signature, σ, together. Although this allows $\mathcal{S}$ to always make a valid signature, it is never allowed to make an invalid signature in an honest execution of **Share Generation**. Based on the signature shares, the parties can learn σ from **Share Combination**, although if parties have been cheating in **Shares Generation** they will be exposed during **Share Combination**. We observe that the choice of shares binds $\mathcal{S}$ to a certain set of dishonest parties. Note that by assuming both $\mathcal{F}_{\mathsf{Sig}}$ and $\mathcal{F}_{\mathsf{TSig}}$ to be *global* UC functionalities, it allows other UC functionalities, both local and global, to verify signatures on them. This becomes essential to allow interaction with our, global, ledger functionalities.

Functionality $\mathcal{F}_{\mathsf{TSig}}$

$\mathcal{F}_{\mathsf{TSig}}$ is parameterized with an ideal adversary $\mathcal{S}$, a set of signers $\mathcal{P}$ and functionalities $\mathcal{F}$, a verifiers $\mathcal{V}$ (which automatically contains $\mathcal{P}$ and $\mathcal{F}$) and a set of corrupted signers $I \subset \mathcal{P}$. $\mathcal{F}_{\mathsf{TSig}}$ has two internal lists $\mathtt{Sh}$ and $\mathtt{Sig}$.

Key Generation: Upon receiving a message $(keygen)$ from each $\mathcal{P}_i \in \mathcal{P}$ or a functionality $\mathcal{F}_j \in \mathcal{F}$ hand $(keygen)$ to the adversary $\mathcal{S}$. Upon receiving $(verificationkey)\mathsf{vk}$ from $\mathcal{S}$, if $(\cdot, \mathsf{vk})$ was not recorded yet then output $(verificationkey)\mathsf{vk}$ to each $\mathcal{P}_i \in \mathcal{P}$ (or to $\mathcal{F}_j$), and record the pair $(\mathcal{P}, \mathsf{vk})$. If vk was recorded before then output $(Abort)$ to $\mathcal{S}$ and stop.

Share Generation: Upon receiving a message $(sign)m, \mathsf{vk}$ from all honest parties or a functionality $\mathcal{F}_j \in \mathcal{F}$ send $(sign)m$ to $\mathcal{S}$. Upon receiving $(signature)m, \rho, \sigma, J, f$ from $\mathcal{S}$, verify that
- no entry $(m, \rho, J', \mathsf{vk}')$ with $J' \neq J$ is recorded in $\mathtt{Sh}$, and
- no entry $(m, \sigma, \mathsf{vk}, 0)$ is recorded in $\mathtt{Sig}$ if $J = \emptyset$.

If either is, then output an error message to $\mathcal{S}$ and halt. Else, let $f' = 1$ if $J = \emptyset$ and $f' = f$ otherwise, record the entry $(m, \rho, J, \mathsf{vk})$ in $\mathtt{Sh}$, $(m, \sigma, \mathsf{vk}, f')$ in $\mathtt{Sig}$ and return $(shares)m, \rho$.

Share Combination: Upon receiving a message $(combine)m, \rho, \mathsf{vk}$ from any party in $\mathcal{P}$ or functionality $\mathcal{F}_j \in \mathcal{F}$, find $(m, \rho, J, \mathsf{vk})$ in $\mathtt{Sh}$ and $(m, \sigma, \mathsf{vk}, b)$ in $\mathtt{Sig}$. If $J \neq \emptyset$ then return $(Failure)J$. If $J = \emptyset$ return $(combined)m, \sigma, \mathsf{vk}$. If no entry could be found in $\mathtt{Sh}$ and $\mathtt{Sig}$ then return $(Not - Generated)$.

Signature Verification: Upon receiving a message $(verify)m, \sigma, \mathsf{vk}'$ from some entity in $\mathcal{V}$, hand $(verify)m, \sigma, \mathsf{vk}'$ to $\mathcal{S}$. Upon receiving $(verified)m, \phi$ from $\mathcal{S}$ do:
1. If $\mathsf{vk}' = \mathsf{vk}$ and $(m, \sigma, \mathsf{vk}, 1) \in \mathtt{Sig}$, then set $f = 1$.
2. Else, if $\mathsf{vk}' = \mathsf{vk}$ and $(m, \sigma', \mathsf{vk}, 1) \notin \mathtt{Sig}$ for any σ', then set $f = 0$ and record the entry $(m, \sigma, \mathsf{vk}, 0)$ in $\mathtt{Sig}$.
3. Else, if there is an entry $(m, \sigma, \mathsf{vk}', f') \in \mathtt{Sig}$ recorded, then let $f = f'$.
4. Else, let $f = \phi$ and record the entry $(m, \sigma, \mathsf{vk}', \phi)$ in $\mathtt{Sig}$.

Return $(verified)m, f$.

Fig. 4: Global UC functionality $\mathcal{F}_{\mathsf{TSig}}$ for Threshold Signatures.

Non-interactive zero-knowledge. We us non-interactive zero-knowledge arguments of knowledge, allowing any party to construct a proof that can later be validated by any verifier. We model this in the same way as done by Groth *et al.* [43] and formally define the functionality $\mathcal{F}_{\mathsf{NIZK}}$ for this in Fig. 5 in Sec. A. The functionality $\mathcal{F}_{\mathsf{NIZK}}$ allows any party to prove in zero knowledge that they know a witness w for a public statement x such that $(x, w) \in R$ for a NP relation R.

Functionality $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$

$\mathcal{F}_{\mathsf{NIZK}}$ interacts with parties $\mathcal{P} = \{P_1, ..., P_n\}$ and simulator $\mathcal{S}$ and is parameterized with relation R.

Proof: On input $(\textsc{Prove}, sid, x, w)$ from party P, ignore if $(x, w) \notin R$. Send $(\textsc{Prove}, x)$ to $\mathcal{S}$ and wait for answer $(\textsc{Proof}, \pi)$. Upon receiving the answer store (x, π) and send $(\textsc{Proof}, sid, \pi)$ to P.

Verification: On input $(\textsc{Verify}, sid, x, \pi)$ from $\mathcal{V}$, check whether (x, π) is stored. If not send $(\textsc{verify}, x, \pi)$ to $\mathcal{S}$ and wait for an answer $(\textsc{Witness}, w)$. Upon receiving the answer, check whether $(x, w) \in R$ and in that case, store (x, π). If (x, π) has been stored, return $(\textsc{Verification}, sid, 1)$ to $\mathcal{V}$, else return $(\textsc{Verification}, sid, 0)$.

Fig. 5: UC functionality $\mathcal{F}_{\mathsf{NIZK}}$ for Non-interactive Zero-Knowledge

MPC. Secure Multi-Party Computation (MPC) allows a set of mutually distrusting $\mathcal{P} = \{P_1, \ldots, P_n\}$ to compute any efficiently commutable function $f(x_1, \ldots, x_n) = (y_1, \ldots, y_n)$ where each party P_i supplied private input x_i and received private output y_i. MPC guarantees that the only thing known to party P_i after the computation is x_i and y_i. Multiple security and computational models exist for this, but in this paper we will assume the arithmetic black box model, where computation is a directed acyclic graph of arithmetic operations over a finite field $\mathbb{F}$, where $|\mathbb{F}| = p \geq 2^s$. We assume the UC-security against a *static*, *active/malicious* adversary, who can corrupt up to $n - 1$ parties and who may cause an abort at any point in the computation. We assume an MPC scheme, which is *reactive*, meaning that it is possible to compute $f(\cdot)$,and depending on the output, compute some other function $f'(\cdot)$ on the same input as $f(\cdot)$. This model can for example be realized by the SPDZ protocol [33]. For simplicity we will assume the bracket-notation, where the function to be computed is specified by arithmetic operations on hidden variables. Concretely we assume $[\cdot]$ expresses a value hidden in MPC and on which arithmetic computations can be carried out. I.e. $[x] \cdot [y] + [z]$, expresses the computation $x \cdot y + z$ of values $x, y, z \in \mathbb{F}$.

Outsourced MPC. Typically MPC in the setting we need require a non-constant amount of rounds of communication between *all* pairs of parties (depended on the function to compute). If we have many parties supplying input this can become prohibitively expensive. For this reason we introduce another model of MPC known as *outsourced MPC*. Jakobsen *et al.* [44] shows how to use infor-

mation theoretic operation in conjunction with *any* MPC scheme as described above, to allow a large set of clients $\mathcal{C} = \{C_1, \ldots, C_m\}$ to supply private input to an MPC computation, executed by a small set of servers $\mathcal{P} = \{P_1, \ldots, P_n\}$, and receive private output. Crucially the clients only need to execute a few lightweight operations, bounded by their amount of inputs and outputs, and only need to communicate with the servers in a constant amount of rounds.

Insured MPC. It has been shown [29] that it is impossible to achieve *fairness* in MPC when more than $n/2$ of the parties are corrupted. By fairness we mean that if one party learns their output of the computation, so does the rest of the parties. This is a problem since the party learning the output may be malicious and thus maybe abort the protocol based on what they learned. Baum *et al.* [9] show how to incentivize the completion of an MPC protocol, in a public verifiable manner, through financial incentives enforced on a public ledger. Specifically they showed this is possible to do, based on any MPC scheme fitting the model discussed above. We combine this incentivized notion of MPC with the outsourced notion of MPC in the functionality $\mathcal{F}_{\mathsf{Ident}}$. Concretely this specifies an out-sourced MPC functionality where clients $\mathcal{C} = \{C_1, \ldots, C_m\}$ supply private input that is computed on in MPC by the servers $\mathcal{P} = \{P_1, \ldots, P_n\}$ and where the output of the computation is verifiably shared between the servers in such a manner that the shares can verified by an external verifier $\mathcal{V}$ after the completion of the protocol to identify any potential malicious behaviour. We refer to appendix A.1 for a detailed description of $\mathcal{F}_{\mathsf{Ident}}$ and its interaction with servers and clients.

A.1 Publicly Verifiable MPC Functionality $\mathcal{F}_{\mathsf{Ident}}$

We adopt $\mathcal{F}_{\mathsf{Ident}}$ from [9, 11] but include the following extensions to its interface. Firstly, when realizing $\mathcal{F}_{\mathsf{Ident}}$ with a reactive MPC scheme such as [33, 32], we can amend $\mathcal{F}_{\mathsf{Ident}}$ with a reactive interface as in $\mathcal{F}_{\mathsf{Online}}$ from [32], exposing arithmetic operations over secret values, each identified with a unique *vid*, which are *selectively* input or output to the parties.

In addition to a reactive interface, we permit clients to *securely input* values to $\mathcal{F}_{\mathsf{Ident}}$. This is realized with the secure client input protocol from [44], which permits MPC servers to verify the linear MAC of the client input inside a reactive MPC instance. We wrap this secure client input protocol inside $\mathcal{F}_{\mathsf{Ident}}$ (as in the security proof of [44]) to obtain an input interface which can be called by clients.

Theorem 3. *Functionality $\mathcal{F}_{\mathsf{Ident}}$ (in Figure 6) can be realized by a reactive secure computation scheme permitting linear operations for free and the secure client input protocol from [44].*

Proof. (Proof sketch) The original, non-interactive $\mathcal{F}_{\mathsf{Ident}}$ functionality from [9] can be extended with a reactive interface when realized with a reactive MPC scheme [33, 32] with minor adaptations of the UC-proof in [9]. The secure client input protocol of [44] is information-theoretically secure, and can be instantiated

with *any* MPC scheme with free linear operations, including [33, 32], thereby realizing reactive and client input interfaces of $\mathcal{F}_{\mathsf{Ident}}$ in Figure 6.

Functionality $\mathcal{F}_{\mathsf{Ident}}$

For each session, $\mathcal{F}_{\mathsf{Ident}}$ interacts with servers $\mathcal{P} = \{\mathcal{P}_1, \ldots, \mathcal{P}_n\}$, clients $\mathcal{C} = \{\mathcal{C}_1, \ldots, \mathcal{C}_m\}$ and also provides an interface to register external verifiers $\mathcal{V}$. $\mathcal{S}$ provides a set $I_{\mathcal{P}} \subset [n]$ of corrupt parties and $I_{\mathcal{C}} \subseteq [m]$ of corrupt clients. $\mathcal{F}_{\mathsf{Ident}}$ only interacts with $\mathcal{P}, \mathcal{C}, \mathcal{V}$ and $\mathcal{S}$[a] of the respective session *sid*.

Init: Upon first (INIT, *sid*) by all parties in $\mathcal{P}$ set $\mathtt{rev}, \mathtt{ver}, \mathtt{ref} \leftarrow \emptyset$.
Input: Upon first (INPUT, *sid*, x) by $\mathcal{C}_j$, forward (INPUT, *sid*, $\mathcal{C}_j$) to $\mathcal{S}$. If $\mathcal{S}$ continues, $\mathcal{F}_{\mathsf{Ident}}$ samples *vid*, stores (*vid*, x) and returns (INPUT, *sid*, $\mathcal{C}_j$, *vid*) to all $\mathcal{P}$.
Evaluate: Upon first (EVAL, *sid*, g, $vid_1, ..., vid_p$) by all parties $\mathcal{P}$, if ($vid_1, ..., vid_p$) have been stored internally:
1. Compute $x_{p+1}, ..., x_{p+q} \leftarrow g(x_1, ..., x_p)$, sample $vid_{p+1}, ..., vid_{p+q}$.
2. Store $(vid_{p+1}, x_{p+1}), ..., (vid_{p+q}, x_{p+q})$, return $(vid_{p+1}, ..., vid_{p+q})$ to all parties.

Get Shares: Upon first (GETSHARE, *sid*, *vid*) by $\mathcal{P}_i \in \mathcal{P}$ and if (*vid* , x) is stored:
1. For $\mathcal{P}_i \in I_{\mathcal{P}}$, let $\mathcal{S}$ provide $s_{vid}^{(i)} \in \mathbb{F}$. For $\mathcal{P}_i \in \overline{I_{\mathcal{P}}}$, let $s_{vid}^{(i)} \xleftarrow{\$} \mathbb{F}$ s.t. $x = \sum_{i \in [n]} s_{vid}^{(i)}$.
2. Return (SHARE, *sid*, *vid*, $s_{vid}^{(i)}$) to P_i.

Open with identifiable abort: All interfaces below are specific to a (*vid*, $\cdot$).
Share: Upon first (SHARE, *sid*, *vid*) by $\mathcal{P}_i \in \mathcal{P}$ and if (*vid* , x) is stored, sample shares as in **Get Shares** if not previously done and and store locally.
Optimistic Reveal: Upon (OPTIMIST-OPEN, *sid*, *vid*) by each honest $\mathcal{P}_i$ and if **Share** for (*vid*, x) was run, then send (OUTPUT, *sid*, *vid*, x) to $\mathcal{S}$. If $\mathcal{S}$ continues, send (OUTPUT, *sid*, *vid*, x) to each honest $\mathcal{P}_i$, otherwise send (OUTPUT, *sid*, *vid*, $\perp$).
Reveal: Upon (REVEAL, *sid*, *vid*) by $\mathcal{P}_i$, if $i \notin \mathtt{rev}[vid\,]$ send (*vid*, i, $s_{vid}^{(i)}$) to $\mathcal{S}$.
1. If $\mathcal{S}$ continues, set $\mathtt{rev}[vid] \leftarrow \mathtt{rev}[vid] \cup \{i\}$, send (REVEAL, *sid*, i, $s_{vid}^{(i)}$) to all $\mathcal{P}$.
2. Else if $\mathcal{S}$ sends (REVEAL-NOT-OK, *sid*, *vid*, i, J) with $J \subseteq I_{\mathcal{P}}, J \neq \emptyset$, send (REVEAL-FAIL, *sid*, *vid*, i) to all $\mathcal{P}$ and set $\mathtt{ref}[vid] \leftarrow \mathtt{ref}[vid] \cup J$.

Test Reveal: Upon (TEST-REVEAL, *sid*, *vid*) from a party in $\mathcal{P} \cup \mathcal{V}$
1. If $\mathtt{ref}[vid] \neq \emptyset$, return (REVEAL-FAIL, *sid*, *vid*, $\mathtt{ref}[vid]$)
2. Otherwise return (REVEAL-FAIL, *sid*, *vid*, $[n] \setminus \mathtt{rev}[vid]$).

Allow Verify: Upon (START-VERIFY, *sid*, *vid*, i) from party $\mathcal{P}_i \in \mathcal{P}$ set $\mathtt{ver}[vid] \leftarrow \mathtt{ver}[vid] \cup \{i\}$. If $\mathtt{ver}[vid] = [n]$ then deactivate all interfaces for *vid* except **Test Reveal** and **Verify**.
Verify: Upon (VERIFY, *sid*, *vid*, $z^{(1)}, \ldots, z^{(n)}$) by $\mathcal{V}_i \in \mathcal{V}$ with $z^{(j)} \in \mathbb{F}$:
1. If $\mathtt{ver}[vid] \neq [n]$ then return (VERIFY-FAIL, *sid*, *vid*, $[n] \setminus \mathtt{ver}[vid]$).
2. Else if $\mathtt{ver}[vid] = [n]$ and $\mathtt{rev}[vid] \neq [n]$, send to $\mathcal{V}_i$ what **Test Reveal** sends.
3. Else set $\mathtt{ws} \leftarrow \{j \in [n] \mid z^{(j)} \neq s_{vid}^{(j)}\}$ and return (OPEN-FAIL, *sid*, *vid*, ws).

[a] Throughout **Init**, **Input**, **Evaluate** and **(Get) Share**, $\mathcal{S}$ can at any point abort, upon which $\mathcal{F}_{\mathsf{Ident:rct}}$ sends (ABORT, $\perp$) to all parties and terminates.

Fig. 6: UC functionality $\mathcal{F}_{\mathsf{Ident}}$ for reactive MPC with Publicly Verifiable Output.

Identifiable aborts during the output phase. We provide an overview of the execution of a generic protocol π in the $\mathcal{F}_{\mathsf{Ident}}$-hybrid setting, where π can either obtain the output of an MPC secure evaluation on private client inputs performed by an $\mathcal{F}_{\mathsf{Ident}}$ instance, or identify cheating parties.

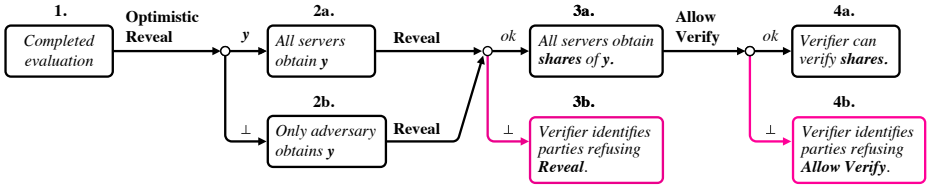


Fig. 7: Output phase of $\mathcal{F}_{\mathsf{Ident}}$ with verifiable output.

Following the secure evaluation on the client inputs, honest parties of π perform the following. Upon sending **Optimistic Reveal** to $\mathcal{F}_{\mathsf{ident}}$, honest parties will either (2a) obtain the output $\mathbf{y} = (y_1, ..., y_m)$, where y_i denotes the output for client $C_i \in \mathcal{C}$, or (2b) only the adversary obtains $\mathbf{y}$. In either state (2a)/(2b), the honest parties of π can *always* reach a state of $\mathcal{F}_{\mathsf{Ident}}$ via **Reveal** and **Allow Verify**, in which either (4a) shares $\mathbf{s}^{(i)}$ for each server $P_i \in \mathcal{P}$ are received by all parties, that are verifiable by by $\mathcal{V}$ and from which $\mathbf{y} = \sum_{i \in [n]} \mathbf{s}^{(i)}$ can be reconstructed, or (3b)/(4b) the verifier $\mathcal{V}$ can identify cheating servers.

The interfaces of $\mathcal{F}_{\mathsf{Ident}}$ exposed to the public verifier $\mathcal{V}$ are central to the arbitration of an abort in protocol π. Here, a smart contract playing the role of public verifier $\mathcal{V}$ can identify the set of cheating servers therefore enforce a financial penalty agreed upon prior to the adversary learning $\mathbf{y}$.

B Ledger Functionalities

B.1 Public ledger functionality

In Figure 8 we describe the ideal functionality $\mathcal{F}_{\mathsf{Ledger}}$. It reflects a general public ledger, with the support for transfers of tokens through signatures, along with Turing complete smart contracts, modeled as arithmetic circuits over $\mathbb{F}$. It requires access to the global UC functionalities of $\mathcal{F}_{\mathsf{Clock}}$, for a notion of rounds, and $\mathcal{F}_{\mathsf{(T)Sig}}$ for signature validation.

Beyond its authenticated bulletin board functionality, on which it is based, $\mathcal{F}_{\mathsf{Ledger}}$ parses all the newly received, signed messages and updates its public state accordingly on the first activation of each $\mathcal{F}_{\mathsf{Clock}}$ round. In addition to authenticated messages, we define its public state to include a public ledger over a default token universe, maintaining balances associated with each signature verification key observed in the authenticated message list. Furthermore, $\mathcal{F}_{\mathsf{Ledger}}$ will maintain public state of *smart contracts instances*, each deployed with a transition function encoded as arithmetic circuits.

Functionality $\mathcal{F}_{\mathsf{Ledger}}$

$\mathcal{F}_{\mathsf{Ledger}}$ interacts with global functionalities $\mathcal{F}_{\mathsf{Clock}}$, $\mathcal{F}_{\mathsf{Sig}}$, $\mathcal{F}_{\mathsf{TSig}}$. It is parameterized by a token universe $\mathbb{T} = \{\tau_0, ..., \tau_t\}$ and maintains public ledger state $\mathcal{L} : \{0,1\}^* \to \mathbb{Z}^{|\mathbb{T}|}$, public contract states $\Gamma : \mathbb{Z} \to \{0,1\}^*$ and a contract counter $\mathsf{ctr} \in \mathbb{Z}$. $\mathcal{F}_{\mathsf{Ledger}}$ has an initially empty list $\mathcal{M}$ of messages posted to the authenticated bulletin board. Further, it interacts with committee parties $\mathcal{Q} = \{Q_1, ..., Q_q\}$.

Upon each activation $\mathcal{F}_{\mathsf{Ledger}}$ first sends a message $(\textsc{Read}, sid)$ to $\mathcal{F}_{\mathsf{Clock}}$. If ν has changed since the last call to $\mathcal{F}_{\mathsf{Clock}}$, then it parses all messages in $\mathcal{M}' \leftarrow \mathcal{M} \setminus \mathcal{M}_{\mathsf{read}}$ in listed order as follows:

Init: Upon parsing $((\textsc{Init}, sid, \mathcal{L}^{\mathsf{init}}), \mathsf{vk}) \in \mathcal{M}'$, set $\mathcal{L} \leftarrow \mathcal{L}^{\mathsf{init}}$, deactivate the parsing of Init messages and activate parsing of Transfer, Deploy, Call messages.

Transfer: Upon parsing $((\textsc{Transfer}, sid, \bar{\mathbf{v}}, \mathsf{vk}_{\mathsf{rcv}}), \mathsf{vk}) \in \mathcal{M}'$, assert $\mathcal{L}[\mathsf{vk}] \geq \bar{\mathbf{v}}$. Set $\mathcal{L}[\mathsf{vk}_{\mathsf{rcv}}] \leftarrow \mathcal{L}[\mathsf{vk}_{\mathsf{rcv}}] + \bar{\mathbf{v}}$ and $\mathcal{L}[\mathsf{vk}] \leftarrow \mathcal{L}[\mathsf{vk}] - \bar{\mathbf{v}}$.

Deploy Contract: Upon parsing $((\textsc{Deploy}, sid, \gamma, T), \mathsf{vk}) \in \mathcal{M}'$, parse initial state $\gamma \in \{0,1\}^*$ and T as an arithmetic circuit over $\mathbb{F}$ of maximum depth d_T. Update $\Gamma \leftarrow \Gamma \cup \{(\mathsf{cn} = \mathsf{ctr}, (\gamma, \bar{\mathbf{0}}, T))\}$ and contract id counter $\mathsf{ctr} \leftarrow \mathsf{ctr} + 1$.

Call Contract: Upon parsing $((\textsc{Call}, sid, (\mathsf{cn}, \mathsf{fn}, x, \bar{\mathbf{v}})), \mathsf{vk}) \in \mathcal{M}'$, assert $\mathcal{L}[\mathsf{vk}] \geq \bar{\mathbf{v}}$. Read $\mathcal{F}_{\mathsf{Clock}}$ round ν, obtain contract state, balances and circuit $(\gamma, \bar{\mathbf{w}}, T) \leftarrow \Gamma[\mathsf{cn}]$ and evaluate circuit T on inputs $(\nu \,|\, \gamma \,|\, \bar{\mathbf{w}} \,|\, \mathsf{cn}, \mathsf{fn}, x, \bar{\mathbf{v}} \,|\, \mathsf{vk})$, which outputs an encoding of a state transition ts, $\mathcal{L} \mid \gamma \mid \bar{\mathbf{w}} \to^{\mathsf{ts}} \mathcal{L}' \mid \gamma' \mid \bar{\mathbf{w}}'$, updating ledger, contract state and balance.

1. T is permitted "callback" gates which specify:
   a. Fragments of state $\mathcal{L} \mid \Gamma$ to read during evaluation of T.
   b. External functionality $\mathcal{F}$ and message m to send:
      - Forward $(\textsc{ExtCall}, sid, \mathcal{F}, \mathsf{m})$ to all $\mathcal{Q}$ who output this forwarded message.
      - Upon $(\textsc{CallBack}, sid, \mathsf{ret})$ from each $\mathcal{Q}$, write replies to call-back gate; the majority response from $\mathcal{Q}$ is read by the circuit upon continuation.
2. On completed evaluation of T, assert:
   a. Preservation of tokens: $\bar{\mathbf{w}} + \sum_{\mathsf{vk} \in \mathsf{dom}(\mathcal{L})} \mathcal{L}[\mathsf{vk}] = \bar{\mathbf{w}}' + \sum_{\mathsf{vk} \in \mathsf{dom}(\mathcal{L})} \mathcal{L}'[\mathsf{vk}]$
   b. No outflow from non-calling accts: $\forall \mathsf{vk}' \in \mathsf{dom}(\mathcal{L}), \mathsf{vk}' \neq \mathsf{vk} : \mathcal{L}'[\mathsf{vk}'] \geq \mathcal{L}[\mathsf{vk}']$.
3. Set $\mathcal{L} \leftarrow \mathcal{L}'$ and $\Gamma[\mathsf{cn}] \leftarrow (\gamma', \bar{\mathbf{w}}', T)$.

After parsing $\mathcal{M}'$, it sets $\mathcal{M}_{\mathsf{read}} \leftarrow \mathcal{M}$ and sends $(\textsc{Update}, sid)$ to $\mathcal{F}_{\mathsf{Clock}}$.

Post: Upon receiving $(\textsc{Post}, sid, m, \mathsf{vk}, \sigma)$ from some entity contact the instance of $\mathcal{F}_{\mathsf{Sig}}$ or $\mathcal{F}_{\mathsf{TSig}}$ belonging to vk. If σ verifies for m and vk then send $(\textsc{Post}, sid, m, \mathsf{vk}, \sigma)$ to $\mathcal{S}$ and append (m, vk) to the list $\mathcal{M}$.

Read: Upon receiving $(\textsc{Read}, sid)$ from some entity, return $\mathcal{M}$.

Fig. 8: Functionality $\mathcal{F}_{\mathsf{Ledger}}$ for Public Ledger and Smart Contracts.

Interaction with UC functionalities. We permit smart contracts deployed to $\mathcal{F}_{\mathsf{Ledger}}$ to pass messages to external UC functionalities. This is required in order for a smart contract instance to evaluate the verification of proofs generated by a $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$ instance or shares output by $\mathcal{F}_{\mathsf{Ident}}$. Interaction in the GUC model is permitted for global functionality $\mathcal{F}_{\mathsf{Ledger}}$ and other global UC functionalities,

such as $\mathcal{F}_{\mathsf{Clock}}$. However, lifting the model of $\mathcal{F}_{\mathsf{Ident}}$ or $\mathcal{F}_{\mathsf{NIZK}}^{\mathcal{R}}$ to global functionalities greatly complicates the definition of any functionality realized in the $\mathcal{F}_{\mathsf{Ident}}$, $\mathcal{F}_{\mathsf{NIZK}}^{\mathcal{R}}$-hybrid setting, as the simulator can no longer equivocate outputs from $\mathcal{F}_{\mathsf{Ident}}$ without simulating its internal state as a hybrid functionality, and extraction of a global $\mathcal{F}_{\mathsf{NIZK}}^{\mathcal{R}}$ would imply a realization by less efficient constructions.

Although we do not model consensus details with $\mathcal{F}_{\mathsf{Ledger}}$, we argue that such a protocol must ultimately realized in the presence of an honest majority committee. Thus, we adopt this assumption with an honest-majority committee of dummy parties $\mathcal{Q} = \{Q_1, ..., Q_q\}$ interacting with $\mathcal{F}_{\mathsf{Ledger}}$, that *forward* verification calls between $\mathcal{F}_{\mathsf{Ledger}}$ and the environment $\mathcal{Z}$. Concretely, we permit the deployed contract circuits to feature *call-back* gates, which indicate an external functionality and message $(\mathcal{F}, \mathsf{m})$ that is forwarded to $\mathcal{Q}$ by $\mathcal{F}_{\mathsf{Ledger}}$.

- Upon receiving (ExtCall, *sid*, $\mathcal{F}$, m) from $\mathcal{F}_{\mathsf{Ledger}}$, an honest party in $\mathcal{Q}$ then returns this message to $\mathcal{Z}$ and waits for a response.
- Upon input (CallBack, *sid*, $\mathcal{F}$, ret) from $\mathcal{Z}$ to the same party $Q \in \mathcal{Q}$, it forwards this message to $\mathcal{F}_{\mathsf{Ledger}}$, which writes the majority response to the call-back gate.

The utility of forwarding $(\mathcal{F}, \mathsf{m})$ to the environment via dummy parties $\mathcal{Q}$ becomes immediate in the $\mathcal{F}$, $\mathcal{F}_{\mathsf{Ledger}}$-hybrid setting: here, the parties in the roles of $\mathcal{Q}$, upon receiving (ExtCall, *sid*, $\mathcal{F}$, m) from $\mathcal{F}_{\mathsf{Ledger}}$ will call hybrid functionality $\mathcal{F}$ with message m, and return the response to $\mathcal{F}_{\mathsf{Ledger}}$. If $\mathcal{Q}$ maintains an honest majority, we obtain correctness of the verification replies returned to $\mathcal{F}_{\mathsf{Ledger}}$. We emphasize that this is a necessary modelling artifact arising from the constraints of the GUC-framework: in actual realizations we argue the parties in $\mathcal{Q}$ are the same parties which jointly realize the underlying ledger functionality as mining or staking parties.

B.2 Confidential ledger functionality

In Fig. 9 we describe the confidential token ledger functionality, $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ we require in our main construction. $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$. It assume access to the $\mathcal{F}_{\mathsf{Ledger}}$ functionality in Fig. 8.

C Protocols

We detail the various protocol realizations of our scheme and their supporting smart contract programs.

C.1 Protocol realizing $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$

In Fig. 10 we show how to realize our confidential token functionality $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ from Fig. 9 on any Turing complete ledger, with the help of the smart contract $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ of Fig. 11.

Functionality $\mathcal{F}_{\underline{\mathsf{CLedger}}}$

$\mathcal{F}_{\underline{\mathsf{CLedger}}}$ interacts with parties $\mathcal{C} = \{C_1, ..., C_p\}$. It is parameterized with token universe $\mathbb{T}$ and max. balance $\bar{\mathbf{v}}_{\mathsf{max}} \in \mathbb{Z}^{|\mathbb{T}|}$ and maintains public ledgers $\mathcal{L}$ and $\mathcal{L}_{\mathsf{Conf}}$, where $\mathcal{L}_{\mathsf{Conf}}$ maps account keys to confidential coins with hidden balances. The functionality is registered at global $\mathcal{F}_{\mathsf{Clock}}$.

Public ledger states are updated at the beginning of each clock round. On each activation, $\mathcal{F}_{\underline{\mathsf{CLedger}}}$ reads $\mathcal{F}_{\mathsf{Clock}}$ and if ν is increased since the last activation, sets $\mathcal{L} \leftarrow \mathcal{L}'$, $\mathcal{L}_{\mathsf{Conf}} \leftarrow \mathcal{L}'_{\mathsf{Conf}}$. Initially, only *GenAcct* and *Init* interfaces are activated.

GenAcct: Upon (GenAcct, *sid*) from C, forward (GenAcct, *sid*, C) to $\mathcal{S}$. Upon obtaining fresh vk from $\mathcal{S}$, set $\mathcal{K}[C] \leftarrow \mathcal{K}[C] \cup \{\mathsf{vk}\}$. Return (AcctKey, *sid*, vk).

Init: Upon receiving (InitLedger, *sid*, $\mathcal{L}_{\mathsf{Init}}, \mathsf{vk}$) from any $C_i \in \mathcal{C}$, forward to $\mathcal{S}$. Set $\mathcal{L}' \leftarrow \mathcal{L}_{\mathsf{Init}}$ and deactivate *Init* and activate all other interfaces.

Transfer: Upon (Transfer, $\bar{\mathbf{v}}, \mathsf{vk}_{\mathsf{rcv}}, \mathsf{vk}$) from C,
- Assert $\mathsf{vk} \in \mathcal{K}[C]$ and forward message (Transfer, $\bar{\mathbf{v}}, \mathsf{vk}_{\mathsf{rcv}}, \mathsf{vk}$) to $\mathcal{S}$.
- If $\mathcal{L}'[\mathsf{vk}] \geq \bar{\mathbf{v}}$, set $\mathcal{L}'[\mathsf{vk}_{\mathsf{rcv}}] \leftarrow \mathcal{L}'[\mathsf{vk}_{\mathsf{rcv}}] + \bar{\mathbf{v}}$ and $\mathcal{L}'[\mathsf{vk}] \leftarrow \mathcal{L}'[\mathsf{vk}] - \bar{\mathbf{v}}$.

Mint: Upon (Mint, *sid*, $\bar{\mathbf{v}}, \mathsf{vk}$) from C,
1. Assert $\mathcal{L}'[\mathsf{vk}] \geq \bar{\mathbf{v}}$ and forward (Mint, *sid*, $\bar{\mathbf{v}}, \mathsf{vk}$) to $\mathcal{S}$ and wait for id from $\mathcal{S}$.
2. Set $\mathcal{L}'_{\mathsf{Conf}}[\mathsf{vk}] \leftarrow \mathcal{L}'_{\mathsf{Conf}}[\mathsf{vk}] \cup \{\langle \mathsf{id}, \bar{\mathbf{v}} \rangle\}$ & $\mathcal{L}'[\mathsf{vk}] \leftarrow \mathcal{L}'[\mathsf{vk}] - \bar{\mathbf{v}}$, return (Minted, *sid*, id).

Confidential Transfer: Upon (ConfTfr, *sid*, $\mathsf{vk}_{\mathsf{rcv}}, \mathsf{id}_1, \mathsf{id}_2, \bar{\mathbf{v}}'_1, \bar{\mathbf{v}}'_2$) from C,
1. Assert $\exists \mathsf{vk} \in \mathcal{K}[C] : \langle \mathsf{id}_i, \bar{\mathbf{v}}_i \rangle \in \mathcal{L}'_{\mathsf{Conf}}[\mathsf{vk}]$ for $i \in \{1, 2\}$.
2. Assert $\bar{\mathbf{v}}_1 + \bar{\mathbf{v}}_2 = \bar{\mathbf{v}}'_1 + \bar{\mathbf{v}}'_2$ and $\bar{\mathbf{v}}_i \leq \bar{\mathbf{v}}_{\mathsf{max}}$ for $i \in \{1, 2\}$.
3. Forward (ConfTfr, *sid*, $\mathsf{vk}_{\mathsf{rcv}}, \mathsf{id}_1, \mathsf{id}_2$) to $\mathcal{S}$, and wait for $(\mathsf{id}'_1, \mathsf{id}'_2)$.
4. For $i \in \{1, 2\}$:
   - Set $\mathcal{L}'_{\mathsf{Conf}}[\mathsf{vk}] \leftarrow \mathcal{L}'_{\mathsf{Conf}}[\mathsf{vk}] \setminus \{\langle \mathsf{id}_1, \bar{\mathbf{v}}_1 \rangle, \langle \mathsf{id}_2, \bar{\mathbf{v}}_2 \rangle\} \cup \{\langle \mathsf{id}'_2, \bar{\mathbf{v}}'_2 \rangle\}$
   - Set $\mathcal{L}'_{\mathsf{Conf}}[\mathsf{vk}_{\mathsf{rcv}}] \leftarrow \mathcal{L}'_{\mathsf{Conf}}[\mathsf{vk}_{\mathsf{rcv}}] \cup \{\langle \mathsf{id}'_1, \bar{\mathbf{v}}'_1 \rangle\}$.
5. If $\mathsf{vk}_{\mathsf{rcv}} \in \mathcal{K}[C']$ s.t. $C' \in \mathcal{I}$, send $(\langle \mathsf{id}'_1, \bar{\mathbf{v}}'_1 \rangle)$ to $\mathcal{S}$. Return (Change, *sid*, id'_2).

Confidential Receive: Upon (ConfRcv, *sid*) from C,
- Return (Received, *sid*, $(\mathsf{vk}_1, \langle \mathsf{id}_1, \bar{\mathbf{v}}_1 \rangle), ..., (\mathsf{vk}_l, \langle \mathsf{id}_l, \bar{\mathbf{v}}_l \rangle)$), containing coins sent to C since the last call, where $\mathsf{vk}_i \in \mathcal{K}[C]$ for $i \in [l]$

Redeem: Upon (ConfRdm, *sid*, id) from C,
1. Assert $\exists \mathsf{vk} \in \mathcal{K}[C] : \langle \mathsf{id}, \bar{\mathbf{v}} \rangle \in \mathcal{L}'_{\mathsf{Conf}}[\mathsf{vk}]$.
2. Remove $\langle \mathsf{id}, \bar{\mathbf{v}} \rangle$ from $\mathcal{L}'_{\mathsf{Conf}}[\mathsf{vk}]$ and set $\mathcal{L}'[\mathsf{vk}] \leftarrow \mathcal{L}'[\mathsf{vk}] + \bar{\mathbf{v}}$.
3. Send (ConfRdm, *sid*, $\langle \mathsf{id}, \bar{\mathbf{v}} \rangle, \mathsf{vk}$) to $\mathcal{S}$.

GetLedger: Upon (GetLedger, *sid*), compute sanitized $\mathcal{L}''_{\mathsf{Conf}}$ such that coin balances are removed from $\mathcal{L}_{\mathsf{Conf}}$. Return $\mathcal{L}$, $\mathcal{L}''_{\mathsf{Conf}}$.

Fig. 9: Functionality $\mathcal{F}_{\underline{\mathsf{CLedger}}}$ for Confidential Ledgers.

Theorem 1. *Protocol $\Pi_{\underline{\mathsf{CLedger}}}$ GUC-realizes functionality $\mathcal{F}_{\underline{\mathsf{CLedger}}}$ in the $\mathcal{F}_{\mathsf{Clock}}$, $\mathcal{F}_{\mathsf{Ledger}}$, $\mathcal{F}_{\mathsf{NIZK}}$, $\mathcal{F}_{\mathsf{Setup}}$, $\mathcal{F}_{\mathsf{Sig}}$-hybrid model against any PPT-adversary corrupting any minority of committee $\mathcal{Q}$.*

Proof (Proof of Theorem 1). We construct a simulator $\mathcal{S}$ that interacts with $\mathcal{A}$, hybrid functionalities $\mathcal{F}_{\mathsf{Ledger}}$, $\mathcal{F}_{\mathsf{NIZK}}$ and global functionalities $\mathcal{F}_{\mathsf{Clock}}$, $\mathcal{F}_{\mathsf{Sig}}$ such that $\mathcal{F}_{\underline{\mathsf{CLedger}}} \circ \mathcal{S} \approx \Pi_{\underline{\mathsf{CLedger}}} \circ \mathcal{A}$ for any PPT environment $\mathcal{Z}$.

Concretely, to create an interaction indistinguishable from a protocol transcript in the composed setting, we construct a simulator $\mathcal{S}$ that generates valid messages for global $\mathcal{F}_{\mathsf{Ledger}}$ from simulated honest client activations and extracts inputs from dishonest messages and forwards these to ideal functionality $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$. This ensures consistency of $\mathcal{A}$'s view of $\mathcal{F}_{\mathsf{Ledger}}$ with the state of $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ during the simulated protocol execution.

On an honest GenAcct input, $\mathcal{S}$ generates a fresh signature verification key for the honest client from $\mathcal{F}_{\mathsf{Sig}}$, which it stores. For any subsequent honest input to $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ which is forwarded to $\mathcal{S}$, the simulator can generate and post verifying messages global functionality $\mathcal{F}_{\mathsf{Ledger}}$.

For honest InitLedger, Transfer inputs, generating verifying messages to post on $\mathcal{F}_{\mathsf{Ledger}}$ is trivial for $\mathcal{S}$, as it generates and stores signature verification keys for honest clients. On observing dishonest InitLedger, Transfer messages on $\mathcal{F}_{\mathsf{Ledger}}$ and asserting that they are accepted by $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$, the simulator can extract all dishonest inputs to forward to $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$, as these messages are posted to $\mathcal{F}_{\mathsf{Ledger}}$ in cleartext.

On an honest Mint input, $\mathcal{S}$ must generate and send a verifying Call message to $\mathcal{F}_{\mathsf{Ledger}}$ with the minted amount $\bar{\mathbf{v}}$ which activates the deployed $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ contract instance to mint a fresh confidential token. Since $\mathcal{S}$ simulates protocol messages from honest clients, it can generate a valid commitment for $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ itself and store its opening $(\bar{\mathbf{v}}, r)$. With the commitment opening, it obtains a verifying NIZK via $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$ proving $\mathcal{R}(\bar{\mathbf{v}}, c; r) = \{c = \mathbf{g}^{\bar{\mathbf{v}}} h^r\}$. For a dishonest mint message observed on $\mathcal{F}_{\mathsf{Ledger}}$ by $\mathcal{S}$, the simulator trivially extracts inputs for $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$: both minted amount and minting account key in the Call message sent to activate minting in the $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ contract instance are observable in cleartext on $\mathcal{F}_{\mathsf{Ledger}}$.

On an honest ConfTransfer input, $\mathcal{S}$ generates valid coin commitments and rangeproofs for a call activating ConfTrfr on the $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ contract instance deployed to $\mathcal{F}_{\mathsf{Ledger}}$. For an *honest sender and honest recipient*, $\mathcal{S}$ needs to generate output coin commitments that are consistent with the chosen input coins for the simulated protocol. Here, $\mathcal{S}$ always possesses the openings of the input coin commitments:

- *Coins previously received from an honest sender* were generated by $\mathcal{S}$ with arbitrary openings previously generated by $\mathcal{S}$: since $\mathcal{S}$ does not learn the transfer amount for confidential transfer between honest users, it generates output coins commitments with *arbitrary balances*, such that the product equality of input and output commitments holds: $\mathbf{g}^{\bar{\mathbf{v}}_1} h^{r_1} \mathbf{g}^{\bar{\mathbf{v}}_2} h^{r_2} = \mathbf{g}^{\bar{\mathbf{v}}'_1} h^{r'_1} \mathbf{g}^{\bar{\mathbf{v}}'_2} h^{r'_2}$. However, since simulated setup functionality $\mathcal{F}_{\mathsf{Setup}}$ samples $s \leftarrow\!\$\, \mathbb{F}_p$ and outputs $h = g^s$, coins generated by $\mathcal{S}$ can later be *equivocated* to any value.
- *Coins previously received from a dishonest sender* feature openings sent directly to the receiving honest client simulated by $\mathcal{S}$ in the simulated protocol.

Thus, for an honest confidential transfer sending coins to another honest party, $\mathcal{S}$ generates output coin commitments with arbitrary chosen coin balances, stores their openings and obtains verifying rangeproofs via $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$. For an *honest sender and dishonest recipient*, $\mathcal{S}$ learns the transferred amount from $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$, and

can generate output coin commitments with correct balances and post these to $\mathcal{F}_{\mathsf{Ledger}}$ (with equivocation of the input coin commitments if necessary). Then, it forwards the coin openings as a simulated protocol message to the dishonest recipient.

Finally for a *dishonest sender and dishonest recipient* $\mathcal{S}$ can extract openings for all coins generated by the dishonest sender since they all have associated NIZK's obtained by sending valid coin openings to the simulated $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$ instance. Thus, the simulator can forward the transferred amounts to $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$. For a *dishonest sender and honest recipient*, the simulated honest recipient obtains transferred coin commitment opening as a protocol message, allowing $\mathcal{S}$ to forward this input to $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$.

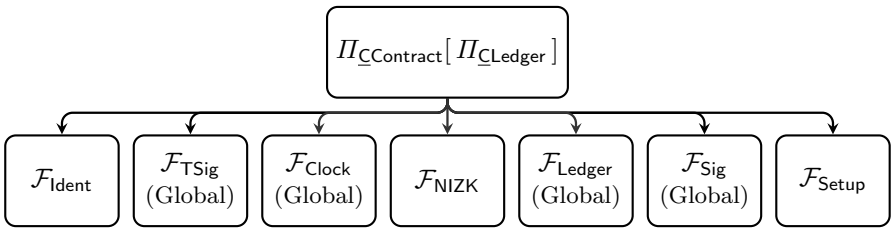
On an honest ConfReceive, the simulator must have previously provided inputs to $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ for confidential transfers *initiated* by dishonest parties, as previously described. On a *dishonest confidential receive*, $\mathcal{S}$ will have previously sent the openings of the honestly sent coins to the dishonest recipient as a protocol message, in addition to having generated valid coins and rangeproofs observable on $\mathcal{F}_{\mathsf{Ledger}}$.

On an honest ConfRedeem, if the redeemed coin was originally sent by a dishonest user, $\mathcal{S}$ must have also received its opening as a protocol message , as it simulates the role of the honest user in the protocol execution. Otherwise, the redeemed coin must have been sent by an honest user, and can thus be equivocated by $\mathcal{S}$. Thus, with the equivocated coin opening, $\mathcal{S}$ can produce a verifying NIZK for the honest redeem action in the simulated protocol view. On a *dishonest redeem*, $\mathcal{S}$ observes the redeemed value publicly on $\mathcal{F}_{\mathsf{Ledger}}$, and can thus forward this input to $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$.

As long as the majority of parties in $\mathcal{Q}$ are honest, verification responses from $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$ are interpreted correctly by the call-back gate on $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$. Thus, the public state of $\mathcal{L}_{\mathsf{Conf}}$ on $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ observed in the simulated protocol view is consistent with the confidential ledger maintained by $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$.

Finally, we note that the *updates* to ledger states induced by client activations are applied at the beginning of each $\mathcal{F}_{\mathsf{Clock}}$ round in both global $\mathcal{F}_{\mathsf{Ledger}}$ and ideal functionality $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$. □

C.2 Protocol realizing $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$



In Fig. 12 and 13 we show how to realize our privacy preserving smart contract functionality $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$ from Fig. 2 on any Turing complete ledger, with

the help of a smart contract with code of $\mathcal{X}_{\mathsf{Lock}}$ of Fig. 14 to manage confidential tokens and $\mathcal{X}_{\mathsf{Collateral}}$ of Fig. 15 to manage underlying collateral. Note that $\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}$ extends $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$, and similarly that contract $\mathcal{X}_{\mathsf{Lock}}$ extends $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$.

Theorem 2. *$\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}[\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}]$ realizes $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}[\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}]$ in the $\mathcal{F}_{\mathsf{Clock}}$, $\mathcal{F}_{\mathsf{Ident}}$, $\mathcal{F}_{\mathsf{Ledger}}$, $\mathcal{F}_{\mathsf{NIZK}}$, $\mathcal{F}_{\mathsf{Setup}}$, $\mathcal{F}_{\mathsf{Sig}}$, $\mathcal{F}_{\mathsf{TSig}}$-hybrid model against any PPT-adversary corrupting at most $n-1$ of the n servers $\mathcal{P}$ statically and any minority of $\mathcal{Q}$.*

Proof. (Theorem 2) We construct a simulator $\mathcal{S}$ that interacts with $\mathcal{A}$, hybrid functionalities $\mathcal{F}_{\mathsf{Ident}}$, $\mathcal{F}_{\mathsf{NIZK}}$, and global functionalities $\mathcal{F}_{\mathsf{Clock}}$, $\mathcal{F}_{\mathsf{Ledger}}$, $\mathcal{F}_{\mathsf{Sig}}$, $\mathcal{F}_{\mathsf{TSig}}$ such that $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}} \circ \mathcal{S} \approx \Pi_{\underline{\mathsf{C}}\mathsf{Ledger}} \circ \mathcal{A}$ for any PPT environment $\mathcal{Z}$.

Upon an honest Init, the simulator $\mathcal{S}$ simulates the roles of the honest parties in the simulated protocol execution, and jointly generates a threshold signature verification key with the dishonest parties via $\mathcal{F}_{\mathsf{TSig}}$. It simulates **GenAcct** and **InitLedger** as in $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$. As $\mathcal{S}$ generates the signature verification key for each honest server, it can call $\mathcal{F}_{\mathsf{Sig}}$ and generate verifying messages for the simulated honest server to post on global $\mathcal{F}_{\mathsf{Ledger}}$, observable by $\mathcal{A}$. Since $\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}$ extends $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$, $\mathcal{S}$ signs messages that initialize contracts $\mathcal{X}_{\mathsf{Lock}}[\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}]$ and $\mathcal{X}_{\mathsf{Collateral}}$, and can authorize collateral deposits to the contract instance $\mathcal{X}_{\mathsf{Collateral}}$ on $\mathcal{F}_{\mathsf{Ledger}}$.

Upon an honest Enroll, the simulator is forwarded the input client coin identifier and account verification key. $\mathcal{S}$ simulates the honest party by generating output masks for which it samples the random openings. Then it determines valid openings for the honest input coin:

- If the honest input coin was previously transferred by a dishonest party, simulator $\mathcal{S}$ can extract its opening from the NIZK range-proof generated via simulated hybrid $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$.
- If the honest input coin was previously transferred by an honest party, $\mathcal{S}$ must have generated the openings itself (See simulator of $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$).

In either case, the simulator sends valid openings of both honest input coins and mask commitments to hybrid $\mathcal{F}_{\mathsf{Ident}}$.

Subsequently, the simulator can simulate a consistent protocol execution of **Verify input** which only aborts if $\mathcal{A}$ provides inputs to simulated hybrid $\mathcal{F}_{\mathsf{Ident}}$ that are inconsistent with the input coin and mask commitments sent to $\mathcal{X}_{\mathsf{Lock}}$ on simulated $\mathcal{F}_{\mathsf{LedgerVM}}$. It simulates the batched sigma protocol to check input consistency in the simulated execution of **Verify input** in $\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}$. Inconsistency of inputs must arise from cheating by $\mathcal{A}$ and results in an abort. As shown in Section 3.1, the probability that the simulated protocol aborts due to inconsistent inputs whilst the ideal functionality continues is negligible in the group order of the Pedersen commitment scheme.

Upon an honest Evaluate and its successful completion, the simulator will jointly sign eval via $\mathcal{F}_{\mathsf{TSig}}$ with the dishonest parties.

Upon an honest Open, the simulator first observes what $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$ outputs, and then will modify the state of the simulated $\mathcal{F}_{\mathsf{Ident}}$ instance, such that the adversary in the simulated protocol observes the masked outputs consistent with what $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$ outputs.

Upon an honest WITHDRAW, the simulator does nothing. At each $\mathcal{F}_{\mathsf{Clock}}$ round during the simulated protocol execution, if the adversary aborts, $\mathcal{S}$ will forward an abort to $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$. If a dishonest party cheats during the **Open** phase of the simulated protocol execution it will be identified by the simulated $\mathcal{F}_{\mathsf{Ident}}$ instance, and its identity is forwarded to $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$ by $\mathcal{S}$.

$\mathcal{S}$ simulates the honest parties of committee $\mathcal{Q}$ in the simulated protocol execution. As long as the majority of parties in $\mathcal{Q}$ are honest, verification responses from $\mathcal{F}_{\mathsf{Ident}}$ are interpreted correctly by the call-back gate on $\mathcal{X}_{\mathsf{Lock}}$, permitting the cheating parties in the simulated protocol execution to be correctly identified during an abort. □

D Applications

To highlight the usefulness of our solution, we here go through some applications of privacy preserving smart contracts in Sec. D.1, how our solution can be used for privacy preserving side-chains in Sec. D.2 and in Sec. D.3 we show how our solution can easily be expanded to allow for privacy preserving cross-chain smart contracts and how these can be used to realize decentralized cross-chain exchange with privacy and without front-running.

D.1 Privacy preserving applications

Several general applications for privacy preserving smart contracts have already been suggested in previous works. We briefly outline some of these here.

Auctions Auctions of digital goods, or digital deeds linked to physical goods, can be constructed simpler and more efficiently than with non-privacy preserving smart contracts. Without privacy preserving smart contracts, auctions will trivially be vulnerable to front-running (since miners will see all bids posted to the blockchain). However, protocols can be constructed to prevent this, e.g. by using a commit-and-open scheme, where bids are committed to by all parties initially. Then the bids are opened and the winner is found. While this works it requires bidders to be online throughout the entire protocol and wait for all other parties. This can in practice cause significant delays and reliability issues, but what is worse is that now *all* bids become publicly visible. Although custom protocols exist for realizing secure decentralized auctions, e.g. on Ethereum [39], these are highly specific on this application and require usage of secure hardware, which has been shown to have significant security issues [77]. However, our solution will allow both first and second price auctions to be executed privately in a way where users only give input once and then either receive their tokens back, or receive the digital good that is being auctioned. Concretely confidential tokens reflecting the maximum bid each user should be transferred to a privacy preserving smart contract along with the good for sale. The smart contract then compares the bids and transfers ownership of the good and handles the payment and refunding, according to code of the smart contract being executed in MPC.

Voting Voting is a highly relevant problem, both in general, but also in the blockchain space in itself. For example it is needed to manage decision making in DAOs and dApps, along with governance situations on layer 1 chains. While directly posting votes to a blockchain would be possible and make auditability easy, although it would completely ruin the privacy aspects such fundamental to elections. However solutions to securely realizing voting on the blockchain exist, such as Polys, which is based on the general electronic voting scheme of Fujioka *et al.* [38]. Using privacy preserving smart contracts it is again easy to do secure voting. Each user simply input a unique identifier for the candidate they wish to vote for and the smart contract tallies up the votes and output the winner.

Identity management Decentralized Identity (DID) management is the idea that, by using blockchains, users remain in charge over how their private attributes (certified by an appropriate authority) are used online. Multiple schemes for this has been suggested such as Sovrin [51] or CanDID [61]. However, these schemes generally only consider leveraging the blockchain for storing user's attribute information. However, using privacy preserving smart contracts would allow integration of user-certified attributes in both the web 2 and web 3 space. Concretely the users could give their hidden certified attributes as input the privacy preserving smart contract, which can validate them privately and use the content of these attributes to affect its business logic. For example the attributes can be used to decide the price of an NFT or to validate whether a user is privilege enough to execute certain commands of the contract.

Mixer Our structure can naturally be extended to allow for a mixing functionality. Imagine users send their confidential tokens to an address that is administered with a distributed key held by the servers. Then the users transfer the confidential tokens they wish to get mixed to this address. Next privately give to the MPC functionality input about the token amounts, the opening information to the commitments along with identification which of commitment (to zero tokens) they want to get updated with their mixed tokens. While several other technologies exist for this, we observe that doing this in MPC allows several advantages that can prevent the mixing to be used for money laundering. Concretely we could imagine that KYC (Know Your Customer) information linked to the users' blockchain address must be given and privately validated against deny-lists, to prevent criminals using this service. Even if deny-lists are not in use, linking to an actual identity could also be leveraged to allow a given user to only get privacy on the first x amount of tokens they mix, and after that, information on the token amount will become public. This is the idea used in Blinder [2] which gives a good compromise between privacy and prevention of impactful illicit activities.

D.2 Anonymous side-chain

Our solution could also be used to construct privacy preserving side-chains. When no server is trying to cheat, there is technically no need for the MPC servers to post anything related to the specific clients and their input to the blockchain, after the *evaluation* phase. Thus the MPC servers can alone realize

a privacy preserving side-chain where they in MPC hold the opening information to the commitments of hidden tokens. Thus users can request transfers to other users in this side-chain, if the servers just use the MPC scheme to keep track of how many tokens each user has. At certain intervals, each user can then just decide to get paid back whatever they hold in the side-chain, by the execution of the *open* and *withdraw* phases. This can be used to enhance the anonymity of hidden transfers, since now *only* the MPC servers know the transaction graph, and yet they do not know the transaction amounts. An interesting observation with this case is also that the side-chain will be faster and cheaper to use than the underlying layer 1 blockchain, since it will only be managed by the MPC servers.

D.3 Cross-chain Exchange

Our protocol presented in Sec. 3 only shows how to confidentially compute on wrapped tokens on a single layer 1 blockchain. However, in this section we will discuss, using ideas from P2DEX [11], how to generalize this to allow confidential computation and transactions *across* multiple layer 1 blockchains.

Inter-chain communication. Constructing confidential smart contacts on with hidden token amounts provide an essential functionality, which can for example be used to facilitates multiple products in DeFi. However, alone it does not facilitate a complete web 3 infrastructure, since the paramount issue of inter-chain communication and token transfer remains. Any inter-token transaction and smart-contract can be emulated by a single blockchain with Turing complete smart contracts using wrapped tokens pegged to their native counterparts. However native tokens necessarily exists on specific blockchains with specific features, advantages and disadvantages. Thus, to fully utilize the power of DeFi, and other use-cases requiring multi-chain interaction, intercommunication between different blockchains has to be possible in an efficient, publicly audible and guaranteed correct way.

Unfortunately this is a hard problem, as even inter-chain or correct off-chain communication, is non-trivial. Solutions facilitating such communication is generally known as “layer 0”. Such inter/off-chain communication is in fact the driving use-case/feature of blockchains like Chainlink, Cosmos and Polkadot. There are also non-blockchains on the market providing such services, such as the aptly named “LayerZero” project. While simple communication between different blockchains is a step in the direction of chain-agnostic DeFi, it does not itself solve the underlying problem of exchanging tokens between chains. That is, the problem of moving native tokens which one party holds on blockchain A into tokens the same party holds on blockchain B. To achieve this it is crucial to notice that unless chain B have authority to mint tokens, depending on what happens on chain A, such “transfer” necessarily entails and exchange between two or more parties. The simple solution to this problem is simply to trust a centralized authority which holds large liquidity of tokens on multiple chains, and offer to facilitate such exchange based on what they deem the market clear-

ing prices (plus a fee) such as CoinBase, Kraken or Binance. This of course goes directly against the ethos of the blockchain and its public audibility, efficiency and guaranteed correctness, and hence much work, both academic and practical has been carried into developing decentralized solutions.

Decentralized exchanges. When it comes to decentralized exchange, multiple approaches exist but generally fall into one of the following families:

P2P Two parties, each with tokens on a chain the other decide, agree on doing an exchange with a certain exchange rate. This is for example the approach used in hash-proofs , where each party make a smart contract embedded with a value a paying out tokens to the recipient's address, once they supply them with a value b s.t. $H(b) = a$. The first party picks the value b and posts their smart contract and waits for the other party posting a similar one, with the same value a. Thus when the first party redeems, the second party will see the value a and be able to redeem as well [71]. This unfortunately requires multiple rounds of on-chain interaction, fees, not to mention the issue of having parties find each other.

Exchange chain A chain contains wrapped tokens pegged to their native counterparts through holding smart contracts on all the native chains. This allows to reduce the cross-chain exchange problem to an on-chain problem, assuming the problem of inter-chain communication has been solved. Concretely the exchange chain will mint tokens once it gets news of new wrapped tokens being added to one of their holding smart contracts on a native chain. Thus a user can for example deposit Ether to the holding contract on Ethereum and the exchange chain mints wrapped Ether and deposit it to the user's exchange account. In a similar manner a burning contract can be used on the exchange chain to destroy wrapped tokens and trigger the holding contract to pay out. With an exchange chain in place there are multiple ways of facilitating exchanges, since now the problem is reduced same-chain exchange:

Order book In the order book approach all orders (e.g. limit orders) are written to the chain and then matched and carried out by a smart contract. Unfortunately this inherently front-running by miners. This approach is for example used by Stellar [37]. Another approach is store use a centralized centralized off-chain service to facilitate the order book, while user's still hold the keys to their tokens until the exchange is carried out. This is for example the approach used by the Binanace DEX [1], 0x [78] and IDEX. Although, IDEX instead of using a dedicated chain, is hosted on common chains like Ethereum or the Binance chain. Thus IDEX facilitates exchanges through a centralized order book and associated smart contract hosted on different native chains. Although IDEX has later evolved into using a mix of an order book approach and AMMs [58]. However, their order-book system is inherently centralized and thus allow the provider to front-run and do rate manipulation, although it protects against front-running by miners.

AMM An AMM is basically a liquidity holding smart contract, allowing exchange between two different tokens. Concretely the smart contract will hold α tokens of type A and β tokens of type B, where the total liquidity is expressed by a constant $k = \alpha \cdot \beta$. The smart contract then facilitates exchange

between tokens of type A and B, with an exchange rate that ensure that the product of the amount of tokens in the contract, k, remains constant. Thus the more tokens of type A is there fewer of token B there will be in the pool and the more expensive tokens of type B will be. Such a scheme is for example deployed in UniSwap. Unfortunately AMMs are highly susceptible to front-running by miners, since orders and exchange rates will be known to miners before they get carried out.

While these approaches solve some issues related to decentralized exchange none of these are unfortunately a silver bullet for users who desire both ease of use, decentralization and front-running resistance [8].

P2DEX. P2DEX [11] is a different system for achieving cross chain exchange, although it can be considered a special case of the order book approach. It uses a set of outsourced MPC servers [31, 44] who threshold control burner addresses, where the clients transfer the tokens they wish to exchange, to compute order matching based on private input of clients. Based on this the servers compute the optimally matched orders, based on a public, but arbitrary, matching algorithm and use the threshold signing keys from the burner addresses in order to carry out the exchange. The fact that the servers and miners don't see the actual orders *before* they have been matched prevents front-running. Unfortunately, the amounts which users wish to exchange (or at least an upper bound on these) will be publicly visible on the blockchain and to the servers. Thus very large order, especially if the exchange only supports a few chains, will be an indicator of the exchanged token falling in value. Furthermore, since there will be a latency in the MPC servers computing and posting the order matching to the blockchains, an adversary could speculate based on such an observation and quickly buy the tokens, expected to increase in value, from another exchange provider.

Adding cross-chain functionality. Like our work, P2DEX also use a set of MPC servers to compute on client's private input. But unlike P2DEX we don't use burner addresses, but instead a holding smart contract Lock, administered by a *single* distributed signing key. But we note that the P2DEX approach will also work with the smart contract based approach. Thus by simply having Lock smart contracts instantiated on multiple blockchains, with different administration keys, these can form the same purpose as the burner addresses in P2DEX. Concretely this can be realized by simply having each client provide a confidential token commitment on each chain they expect to receive some tokens. Note that such a commitment can be of 0 tokens. The MPC servers will then validate all the confidential tokens given to Lock on each of the different chains, through the *verify input* phase. Then one, unified privacy preserving smart contract ConfContract will be executed, which will yield new commitments for each of the relevant clients on each chain. The clients can then use *withdraw* in Lock on each of the different chains to finish the computation and get their confidential tokens on the relevant chains.

This approach could of course also be combined with the mixer idea above, allowing for cross-chain mixers with selective levels of privacy depending on the amounts mixed by a given user.

Doing cross-chain exchange on hidden tokens also has the advantage of allowing parties, with very large amounts of tokens, to carry out an exchange in a slow and continues manner, thus preventing sudden exchange fluctuations. In fact, our system could enforce an upper bound on the amount of tokens to exchange in one round, and automatically split up large orders so they get completed over multiple rounds, instead of just one.

Security. The overall security of this approach follows from P2DEX, although we will also argue that intuitively there is nothing non-trivial to simulation if we adjust our ideal functionalities and protocol to follow this approach. Basically where there is formal cryptography to be proven is in the integration between the different ideal functionalities, in particular when ensuring consistency between the input to outsourced MPC and the commitments transferred to the holding contract. However, using our scheme across multiple chains make no difference in this. The only modelling difference is simply that the ideal blockchain functionalities can no be considered to "wrap" different instances of the same functionality (thus reflecting multiple chains). Such a wrap inherently does not affect secure insofar that it does not contain any logical loopholes.

D.4 Future work

While we construct and prove UC-secure a scheme for decentralized privacy preserving smart contracts, we believe there are multiple paths for future work to explore. An immediate interesting path is to implement and benchmark the system for some of the applications we have discussed. For example, a better formalization of the cross-chain approach, along with an investigation of MPC friendly algorithms for fair matching of exchange orders could allow the realization of a highly secure and private decentralized exchange. For such applications it also becomes important to investigate, the logic of how to use the collateral to punish malicious parties in case they cheat. In particular such that no rational party will end up with a skewed or perverse incentives. In relation to this, it would be interesting to investigate how to integrate Pedersen commitments with MPC in an efficient way, *without* requiring the MPC computation domain to be the same as the Pedersen message space. This could have a great affect on the efficiency if the MPC computation domain is significantly smaller than 256 bit. Currently we require the sharing the opening information of commitments to happen in a P2P manner, off-chain, when transferring hidden tokens. It would be interesting to investigate how to implement hidden tokens in a way that does not require client-to-client communication when doing transfers, while working with the rest our protocol. In relation to this, other ways the overall usability of our system could also be improved is constructing a protocol leveraging other existing results to allow stateless clients. For example through some notion of password authenticated distributed secret sharing [20]. In continuation of this,

investigating how to prevent the use of user-supplied masks for each round of execution private smart contract computation, would also give a great impact on the usability of our solution.

Protocol $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$

$\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$ is run by clients $\mathcal{C}$ and committee $\mathcal{Q}$. The protocol runs in the presence of $\mathcal{F}_{\mathsf{Ledger}}$, $\mathcal{F}^{R}_{\mathsf{NIZK}}$, $\mathcal{F}_{\mathsf{Sig}}$ instances. Initially, only accept inputs GenAcct and InitLedger.

GenAcct: Upon (GenAcct, sid), obtain fresh vk from $\mathcal{F}_{\mathsf{Sig}}$. Set key store to $\mathcal{K} \leftarrow \mathcal{K} \cup \{\mathsf{vk}\}$, and return (NewAcct, sid, vk).

InitLedger: Upon (InitLedger, $sid, \mathcal{L}_{\mathsf{Init}}, \mathsf{vk}$), client C parses $\mathcal{L}_{\mathsf{Init}}$ as a map from a set of signature keys to token balances $\mathbb{G} \mapsto (\mathbb{T} \mapsto \mathbb{Z})$ and asserts $\mathsf{vk} \in \mathcal{K}$.

1. C initializes $\mathcal{F}_{\mathsf{Ledger}}$ with $\mathcal{Q}$ and signs $m = (\textsc{Init}, sid, \mathcal{L}_{\mathsf{Init}})$ via $\mathcal{F}_{\mathsf{Sig}}$ with key vk. Send $(\textsc{Post}, sid, m, \mathsf{vk}, \sigma_{\mathsf{vk}}(m))$ to $\mathcal{F}_{\mathsf{Ledger}}$.
2. C compiles $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$ to initial contract state and circuit (γ, T). Sign $m = (\textsc{Deploy}, sid, \gamma, T, \mathsf{vk})$ via $\mathcal{F}_{\mathsf{Sig}}$ with vk, and send $(\textsc{Post}, sid, m, \mathsf{vk}, \sigma_{\mathsf{vk}}(m))$ to $\mathcal{F}_{\mathsf{Ledger}}$. Ignore further InitLedger inputs and accept all other inputs.

Transfer: Upon $(\textsc{Transfer}, \bar{\mathbf{v}}, \mathsf{vk}_{\mathsf{rcv}}, \mathsf{vk})$, obtain $\mathcal{L}$ from GetLedger procedure. Assert $\mathsf{vk} \in \mathcal{K}$ and $\mathcal{L}[\mathsf{vk}] \geq \bar{\mathbf{v}}$. Sign $m = (\textsc{Transfer}, sid, \bar{\mathbf{v}}, \mathsf{vk}_{\mathsf{rcv}})$ via $\mathcal{F}_{\mathsf{Sig}}$ with key vk and send $(\textsc{Post}, sid, m, \mathsf{vk}, \sigma_{\mathsf{vk}}(m))$ to $\mathcal{F}_{\mathsf{Ledger}}$.

Mint: On $(\textsc{Mint}, sid, \bar{\mathbf{v}}, \mathsf{vk})$, client C,

1. Assert $\mathsf{vk} \in \mathcal{K}$, obtain state $\mathcal{L}, \Gamma$ from $\mathcal{F}_{\mathsf{Ledger}}$ and assert $\mathcal{L}[\mathsf{vk}] \geq \mathbf{v}$.
2. Sample $r \leftarrow\!\!\$\ \mathbb{F}$, compute $c \leftarrow \mathsf{com}(\bar{\mathbf{v}}, r)$ and obtain string π from $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$ where $\mathcal{R}(c, \bar{\mathbf{v}}; r) = \{c = \mathsf{com}(\bar{\mathbf{v}}, r)\}$.
3. Sign $(\textsc{Call}, sid, (\mathsf{cn}, f(\textsc{Mint}), (c, \pi), \bar{\mathbf{v}}))$ via $\mathcal{F}_{\mathsf{Sig}}$ with vk and post to $\mathcal{F}_{\mathsf{Ledger}}$.
4. Set wallet $\mathcal{W}[\mathsf{vk}] \leftarrow \mathcal{W}[\mathsf{vk}] \cup \{\langle \mathsf{id} = c, (\bar{\mathbf{v}}, r)\rangle\}$ and return $(\textsc{Minted}, sid, \mathsf{id})$.

ConfTransfer: On $(\textsc{ConfTrfr}, sid, \mathcal{C}_{\mathsf{rcv}}, \mathsf{vk}_{\mathsf{rcv}}, \{\mathsf{id}_i, \bar{\mathbf{v}}'_i\}_{i\in\{1,2\}})$, client C:

1. Assert $\exists \mathsf{vk}_{\mathsf{src}} \in \mathsf{dom}(\mathcal{W}) : (\mathsf{id}_i, (\bar{\mathbf{v}}_i, r_i)) \in \mathcal{W}[\mathsf{vk}_{\mathsf{src}}]$, $\bar{\mathbf{v}}_1 + \bar{\mathbf{v}}_2 = \bar{\mathbf{v}}'_1 + \bar{\mathbf{v}}'_2$, $\bar{\mathbf{v}}'_i \leq \bar{\mathbf{v}}_{\mathsf{max}}$.
2. For $i \in \{1, 2\}$, sample $r'_i \leftarrow\!\!\$\ \mathbb{F}$ such that $\sum_{i\in\{1,2\}} r'_i = \sum_{i\in\{1,2\}} r_i$ and compute $c'_i = \mathsf{com}(\bar{\mathbf{v}}'_i, r'_i)$ and π_i via $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$ that proves $\mathcal{R}(c'_i; \bar{\mathbf{v}}'_i, r'_i) = \{\bar{\mathbf{v}}'_i \leq \bar{\mathbf{v}}_{\mathsf{max}}\}$
3. Sign and post $(\textsc{Call}, sid, (\mathsf{cn}, f(\textsc{ConfTransfer}), x, 0^t), \mathsf{vk}_{\mathsf{src}})$ to $\mathcal{F}_{\mathsf{Ledger}}$, where $x = (\{c_i, c'_i, \pi_i\}_{i\in\{1,2\}}, \mathsf{vk}_{\mathsf{rcv}})$.
4. Send $(\textsc{ConfTrfr}, sid, \bar{\mathbf{v}}'_1, r'_1, \mathsf{vk}_{\mathsf{src}})$ to $\mathcal{C}_{\mathsf{rcv}}$, which stores it.
5. Set $\mathcal{W}[\mathsf{vk}_{\mathsf{src}}] \leftarrow \mathcal{W}[\mathsf{vk}_{\mathsf{src}}] \cup (\mathsf{id}'_2 = c'_2, (\bar{\mathbf{v}}'_2, r'_2))$ and return $(\textsc{Change}, sid, \mathsf{id}'_2)$.

ConfReceive: On $(\textsc{ConfReceive}, sid)$ client C:

1. For $\mathsf{vk} \in \mathsf{dom}(\mathcal{W})$, retrieve $\{(\bar{\mathbf{v}}_i, r_i, \mathsf{vk}_i)\}_{i\in[l]}$ received from clients since the last ConfReceive input and $\mathcal{L}_{\mathsf{Conf}}$ from $\mathcal{F}_{\mathsf{Ledger}}$.
2. For $(\bar{\mathbf{v}}, r, \mathsf{vk}) \in \{(\bar{\mathbf{v}}, r, \mathsf{vk}_i)\}_{i\in[l]}$, compute $c = \mathsf{com}(\bar{\mathbf{v}}, r)$ and assert $c \in \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}]$.
   - If satisfied, add $(\mathsf{id} = c, (\bar{\mathbf{v}}, r))$ to $\mathcal{W}[\mathsf{vk}]$.
3. Returns $(\textsc{Received}, (\mathsf{vk}_1, \langle \mathsf{id}_1, \bar{\mathbf{v}}_1\rangle), ..., (\mathsf{vk}_l, \langle \mathsf{id}'_l, \bar{\mathbf{v}}'_l\rangle))$ for l' received transfers.

Redeem: On $(\textsc{ConfRdm}, sid, \mathsf{id})$ client C,

1. If $\exists(\mathsf{vk}, \bar{\mathbf{v}}, r) : (\mathsf{id}, (\bar{\mathbf{v}}, r)) \in \mathcal{W}[\mathsf{vk}]$, where $\mathsf{id} = \mathsf{com}(\bar{\mathbf{v}}, r)$.
2. Compute π via $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$ which proves $\mathcal{R}(c, \bar{\mathbf{v}}; r) = \{c = \mathsf{com}(\bar{\mathbf{v}}, r)\}$.
3. Sign and post $(\textsc{Call}, sid, (\mathsf{cn}, f(\textsc{Redeem}), (\bar{\mathbf{v}}, c, \pi), \bar{\mathbf{0}}), \mathsf{vk})$ to $\mathcal{F}_{\mathsf{Ledger}}$.

GetLedger: Upon $(\textsc{GetLedger}, sid)$, client C obtains $(\mathcal{L}, \Gamma)$ and contract id cn from $\mathcal{F}_{\mathsf{Ledger}}$, reads $(\gamma, \mathbf{w}, T) \leftarrow \Gamma[\mathsf{cn}]$, and parses γ as $(\mathcal{L}_{\mathsf{Conf}}, \bar{\mathbf{m}})$. C outputs $(\textsc{Ledger}, sid, \mathcal{L}, \mathcal{L}_{\mathsf{Conf}})$.

ExtCall: Upon $(\textsc{ExtCall}, sid, \mathcal{F}, \mathsf{m})$ received from $\mathcal{F}_{\mathsf{Ledger}}$, party $Q \in \mathcal{Q}$ forwards m to hybrid instance $\mathcal{F}$ and waits. Upon response ret from $\mathcal{F}$, party Q forwards $(\textsc{CallBack}, sid, \mathsf{ret})$ to $\mathcal{F}_{\mathsf{Ledger}}$.

Fig. 10: Protocol $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$ UC-securely realizing $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Ledger}}$

Program $\mathcal{X}_{\underline{\subseteq}\mathsf{CLedger}}$

On input $(\nu \,|\, \gamma \,|\, \bar{\mathbf{w}} \,|\, \mathsf{cn}, \mathsf{fn}, x, \bar{\mathbf{v}} \,|\, \mathsf{vk})$, parses function selector fn and execute function routine with input string $x \in \{0,1\}^*$, parsed according to function descriptions below. Further, parse contract state γ as $\mathcal{L}_{\mathsf{Conf}}$, where $\mathcal{L}_{\mathsf{Conf}} : \mathbb{G}^{\mathsf{vrk}} \to \{\mathbb{G}^{\mathsf{com}}, ...\}$. $\mathcal{X}_{\underline{\subseteq}\mathsf{CLedger}}$ is parameterized with committee $\mathcal{Q}$.

Mint: parse x as (c, π) where $c \in \mathbb{G}$ and $\pi \in \{0,1\}^*$.
1. Send call to $\mathcal{Q}$ with msg for $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$ to verify that π proves $\mathcal{R}(\bar{\mathbf{v}}, c; r) = \{c = \mathbf{g}^{\bar{\mathbf{v}}} h^r\}$.
2. Set $\mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}] \leftarrow \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}] \cup \{c\}$, $\bar{\mathbf{w}} \leftarrow \bar{\mathbf{w}} + \bar{\mathbf{v}}$ and $\mathcal{L}[\mathsf{vk}] \leftarrow \mathcal{L}[\mathsf{vk}] - \bar{\mathbf{v}}$.
3. Output updated $(\mathcal{L}, \gamma' = \mathcal{L}_{\mathsf{Conf}}, \bar{\mathbf{w}})$.

ConfTransfer: parse x as $(c_1, c_2, c_1', c_2', \pi_1, \pi_2, \mathsf{vk}_{\mathsf{rcv}})$ where $c_i, c_i' \in \mathbb{G}$, $\pi_i \in \{0,1\}^*$ for $i \in \{1,2\}$ and $\mathsf{vk}_{\mathsf{rcv}} \in \mathbb{G}$.
1. Assert $\{c_1, c_2\} \in \mathcal{L}^{\mathsf{Conf}}[\mathsf{vk}]$ and that $c_1 \cdot c_2 = c_1' \cdot c_2'$ holds.
2. Send call to $\mathcal{Q}$ with msg for $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$ to verify $\forall i \in \{1,2\}$: π_i proves $\mathcal{R}(c_i'; \bar{\mathbf{v}}_i', r_i') = \{\bar{\mathbf{v}}_i' \leq \bar{\mathbf{v}}_{\mathsf{max}} \wedge c_i' = \mathbf{g}^{\bar{\mathbf{v}}_i'} h^{r_i'}\}$.
3. Set $\mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}] \leftarrow \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}] \backslash \{c_1, c_2\} \cup \{c_2'\}$ and $\mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}_{\mathsf{rcv}}] \leftarrow \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}_{\mathsf{rcv}}] \cup \{c_1'\}$.
4. Output updated $(\mathcal{L}, \gamma' = \mathcal{L}_{\mathsf{Conf}}, \bar{\mathbf{w}})$.

Redeem: parse x as $(\bar{\mathbf{v}}, c, \pi)$, $c \in \mathbb{G}$ and $\pi \in \{0,1\}^*$.
1. Assert $c \in \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}]$ and $\bar{\mathbf{w}} \geq \bar{\mathbf{v}}$.
2. Send call to $\mathcal{Q}$ with msg for $\mathcal{F}^{\mathcal{R}}_{\mathsf{NIZK}}$ to verify π proves $\mathcal{R}(\bar{\mathbf{v}}, c; r) = \{c = \mathbf{g}^{\bar{\mathbf{v}}} h^r\}$.
3. Set $\mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}] \leftarrow \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}] \backslash \{c\}$, $\bar{\mathbf{w}} \leftarrow \bar{\mathbf{w}} - \bar{\mathbf{v}}$.
4. Output updated $(\mathcal{L}, \gamma' = \mathcal{L}_{\mathsf{Conf}}, \bar{\mathbf{w}})$.

Fig. 11: The smart contract code $\mathcal{X}_{\underline{\subseteq}\mathsf{CLedger}}$ for confidential tokens.

I/II: Protocol $\Pi_{\underline{\mathsf{CContract}}}$, extends $\Pi_{\underline{\mathsf{CLedger}}}$

All clients and servers are registered with $\mathcal{F}_{\mathsf{Clock}}$.

Init: On $(\textsc{Init}, sid, g)$ server $P \in \mathcal{P}$,
1. Runs **GenAcct** in $\Pi_{\underline{\mathsf{CLedger}}}$ to generate signature verification key vk, sends to $\mathcal{P}$.
2. Runs **InitLedger** in $\Pi_{\underline{\mathsf{CLedger}}}$ to initialize $\mathcal{F}_{\mathsf{Ledger}}$; here, $P \in \mathcal{P}$ obtains fresh vk.
3. Jointly samples key $\mathsf{vk}_{\mathsf{TSig}}$ via $\mathcal{F}_{\mathsf{TSig}}$ with $\mathcal{P}$.
4. Deploys $\mathcal{X}_{\mathsf{Lock}}[\mathcal{X}_{\underline{\mathsf{CLedger}}}]$ and $\mathcal{X}_{\mathsf{Collateral}}$ to $\mathcal{F}_{\mathsf{Ledger}}$.
   a. Obtains contract instance id's $\mathsf{cn}_{\mathsf{Lock}} = \mathsf{cn}_{\underline{\mathsf{CLedger}}}$ and $\mathsf{cn}_{\mathsf{Coll}}$ from $\mathcal{F}_{\mathsf{Ledger}}$.
   b. Signs and sends $(\textsc{Call}, sid, (\mathsf{cn}_{\mathsf{Lock}}, f(\textsc{Init}), (\mathsf{vk}_{\mathsf{TSig}}), 0^{|\mathbb{T}|}), \mathsf{vk})$ to $\mathcal{F}_{\mathsf{Ledger}}$.
   c. Sends $(\textsc{Call}, sid, (\mathsf{cn}_{\mathsf{Coll}}, f(\textsc{Deposit}), (\mathsf{vk}_{\mathsf{TSig}}), \bar{\mathbf{v}}_{\mathsf{Coll}}), \mathsf{vk})$ to $\mathcal{F}_{\mathsf{Ledger}}$.
5. Initializes $\mathcal{F}_{\mathsf{Ident}}$, asserts circuit depth of $\mathsf{depth}(g) \leq d_T$ and stores it.
6. Updates $\mathcal{F}_{\mathsf{Clock}}$.

Enroll: Upon input $(\textsc{Enroll}, sid, x, \mathsf{id}, \mathsf{vk})$, client $C \in \mathcal{C}$:
1. Asserts $\exists(\mathsf{id}, (\bar{\mathbf{v}}, \bar{r})) \in \mathcal{W}[\mathsf{vk}]$ and $\mathsf{cn}_{\mathsf{Lock}}$, $\mathsf{cn}_{\mathsf{Coll}}$ are in `enroll/coll`.
2. Generate output masks:
   a. Samples and stores $\hat{y}, \hat{\mathbf{w}} = (\hat{w}_1, ..., \hat{w}_{|\mathbb{T}|}), \hat{r} \leftarrow\!\!\$\ \mathbb{F}$.
   b. Computes and stores $\hat{c} \leftarrow \mathsf{com}(\hat{\mathbf{w}}, \hat{s})$.
3. Sends client input and output masks $(x, (\bar{\mathbf{v}}, \bar{r}), (\hat{\mathbf{w}}, \hat{s}))$ to $\mathcal{F}_{\mathsf{Ident}}$.
4. Sends $(\textsc{Call}, sid, (\mathsf{cn}_{\mathsf{Lock}}, f(\textsc{Enroll}), (c = \mathsf{com}(\bar{\mathbf{v}}, \bar{r}), \hat{c}), \bar{\mathbf{0}}), \mathsf{vk})$ to $\mathcal{F}_{\mathsf{Ledger}}$.
5. Removes $(\mathsf{id}, (\bar{\mathbf{v}}, \bar{r}))$ from $\mathcal{W}[\mathsf{vk}]$ and updates $\mathcal{F}_{\mathsf{Clock}}$.

Verify input: Upon input $(\textsc{Execute}, sid)$, if $\mathcal{F}_{\mathsf{Clock}}$ has progressed since last activation and $\mathsf{cn}_{\mathsf{Lock}}$, $\mathsf{cn}_{\mathsf{Coll}}$ are in `enrolled` and `coll` respectively, server $P_i \in \mathcal{P}$ performs:
1. P_i obtains client input coins and masks $\{(c_1, \hat{c}_1), ..., (c_m, \hat{c}_m)\}$ from $\mathcal{F}_{\mathsf{Ledger}}$.
2. For verification of client inputs $\{(\bar{\mathbf{v}}_j, \bar{r}_j, c_{j,})\}_{j\in[m]}$, P_i performs:
   a. Servers interact with $\mathcal{F}_{\mathsf{Ident}}$ and call following interfaces:
   - **Evaluate**: $[\bar{\mathbf{a}}], [\bar{b}], [\gamma] \leftarrow \mathsf{rand}()$[a]
   - **Open** $\gamma \leftarrow [\gamma]$.
   - **Get Shares**: $\bar{\mathbf{a}}^{(i)} = (\bar{a}_1^{(i)}, ..., \bar{a}_{|\mathbb{T}|}^{(i)}), \bar{b}^{(i)}, \{\bar{\mathbf{v}}_j^{(i)} = (\bar{v}_{j,1}^{(i)}, ..., \bar{v}_{j,|\mathbb{T}|}^{(i)}), \bar{r}_j^{(i)}\}_{j\in[m]}$
   a. Local computation of the following and sends resulting shares to all $\mathcal{P}$:
   - $\bar{c}_{\mathbf{a},b}^{(i)} \leftarrow \mathsf{com}(\bar{\mathbf{a}}^{(i)}, \bar{b}^{(i)})$, $\bar{v}_t^{(i)\prime} \leftarrow \bar{a}_t^{(i)} + \sum_{j\in[m]} \bar{v}_{j,t}^{(i)} (\gamma^{(i)})^j$ for $t \in [|\mathbb{T}|]$
   - $\bar{r}^{(i)\prime} \leftarrow \bar{b}^{(i)} + \sum_{j\in[m]} \bar{r}_j^{(i)} (\gamma^{(i)})^j$
   b. Each P_i reconstructs $(\bar{\mathbf{v}}' = \bar{v}'_1, ..., \bar{v}'_{|\mathbb{T}|}, \bar{r}')$, from shares and
   - Asserts: $\prod_{i\in[n]} \bar{c}_{\mathbf{a},b}^{(i)} \cdot \prod_{j\in[m]} (c_{j,\mathsf{in}})^{\gamma^j} = \mathbf{g}^{\bar{\mathbf{v}}'} h^{\bar{r}'}$
3. Servers repeats for the batch verification of client masks $\{(\hat{\mathbf{w}}_j, \hat{s}_j, \hat{c}_j)\}_{j\in[m]}$.
4. Server P_i updates $\mathcal{F}_{\mathsf{Clock}}$.

[a] e.g. XOR circuit evaluated on random inputs.

Fig. 12: Part 1 - Protocol $\Pi_{\underline{\mathsf{CContract}}}$ UC-securely realizing $\mathcal{F}_{\underline{\mathsf{CContract}}}$.

II/II: Protocol $\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}$, extends $\Pi_{\underline{\mathsf{C}}\mathsf{Ledger}}$

Evaluate: After *verify input* and if $\mathcal{F}_{\mathsf{Clock}}$ has progressed, $\mathsf{cn}_{\mathsf{Lock}}$ is in `enrolled`, each server $P_i \in \mathcal{P}$ performs:

1. It interacts with following interfaces of $\mathcal{F}_{\mathsf{Ident}}$.
   a. Runs **Evaluate** on circuit g with secret client inputs $\{(x_j, \bar{\mathbf{v}}_j)\}_{j\in[m]}$.
   b. Runs **Evaluate** to apply masks over output gate values of circuit g:
      - For each $j \in [m]$: $([\,y'_j\,], [\,\bar{\mathbf{w}}'_j\,]) \leftarrow ([\,y_j\,], [\,\bar{\mathbf{w}}_j\,]) + ([\,\hat{y}_j\,], [\,\hat{\mathbf{w}}_j\,])$
   c. Runs **Share** for obtain shares of $\{([\,y'_j\,], [\,\bar{\mathbf{w}}'_j\,])\}_{j\in[m]}$ from $\mathcal{F}_{\mathsf{Ident}}$.
2. Jointly signs $\sigma_{\mathsf{vk}_{\mathsf{TSig}}}(\mathsf{eval})$ with $\mathcal{P}$ via $\mathcal{F}_{\mathsf{TSig}}$: if $\mathcal{F}_{\mathsf{TSig}}$ aborts, runs **abort**.
3. Sends $(\textsc{Call}, sid, (\mathsf{cn}_{\mathsf{Lock}}, f(\textsc{Lock}), (\sigma_{\mathsf{vk}_{\mathsf{TSig}}}(\mathsf{eval})), \bar{\mathbf{0}}), \mathsf{vk})$ to $\mathcal{F}_{\mathsf{Ledger}}$, updates $\mathcal{F}_{\mathsf{Clock}}$.

Open: Upon running *evaluate* and $\mathcal{F}_{\mathsf{Clock}}$ has progressed, each server $P_i \in \mathcal{P}$:

1. Runs **Optimistic Reveal** in $\mathcal{F}_{\mathsf{Ident}}$ for masked outputs $\mathsf{mout} = \{(y'_j, \bar{\mathbf{w}}'_j)\}_{j\in[m]}$.
2. Jointly signs $\mathsf{sig} = \sigma_{\mathsf{vk}_{\mathsf{TSig}}}(\mathsf{mout})$ via $\mathcal{F}_{\mathsf{TSig}}$: if *abort* is returned, run **abort**.
3. Sends $(\textsc{Call}, sid, (\mathsf{cn}_{\mathsf{Lock}}, f(\textsc{Settle}), (\mathsf{mout}, \mathsf{sig}), \bar{\mathbf{0}}), \mathsf{vk})$ to $\mathcal{F}_{\mathsf{Ledger}}$, updates $\mathcal{F}_{\mathsf{Clock}}$.

Withdraw: Upon $(\textsc{Withdraw}, sid)$, each client $C_j \in \mathcal{C}$ performs:

1. Retrieves all masked outputs $\{(y'_{j,1}, \bar{\mathbf{w}}'_{j,1}), ..., (y'_{j,l}, \bar{\mathbf{w}}'_{j,l})\}$ added to $\mathsf{cn}_{\mathsf{Lock}}$ on $\mathcal{F}_{\mathsf{Ledger}}$ since last *withdraw* activation.
2. For each retrieved masked output, reads corresponding mask values $(\hat{y}_j, \hat{\mathbf{w}}_j, \hat{s}_j)$ stored locally and computes $y_j = y'_j - \hat{y}_j$, $\bar{\mathbf{w}}_j \leftarrow (\bar{\mathbf{w}}'_j - \hat{\mathbf{w}}_j)$.
   - Samples id'_j and set $\mathcal{W}[\mathsf{vk}_j] \leftarrow \mathcal{W}[\mathsf{vk}_j] \cup \{(\mathsf{id}'_j, (\bar{\mathbf{w}}_j, -\hat{s}_j))\}$.
3. Returns $(y_{j,1}, \langle \mathsf{id}'_{j,1}, \bar{\mathbf{w}}_{j,1}\rangle), ..., (y_{j,l}, \langle \mathsf{id}'_{j,l}, \bar{\mathbf{w}}_{j,l}\rangle)$.

Abort: Upon receiving $(\textsc{Abort}, sid)$, each $P_i \in \mathcal{P}$ ticks $\mathcal{F}_{\mathsf{Clock}}$:

1. If $\mathsf{cn}_{\mathsf{Lock}}$ is in state `enroll` or `enrolled`,
   signs and sends $(\textsc{Call}, sid, (\mathsf{cn}_{\mathsf{Lock}}, f(\textsc{Abort}), \{0, \bar{\mathbf{0}}\}_{j\in[m]}), \bar{\mathbf{0}}), \mathsf{vk})$ to $\mathcal{F}_{\mathsf{Ledger}}$.
2. Else if $\mathsf{cn}_{\mathsf{Lock}}$ is in state `lock`, run **Reveal** and **Allow Verify** with $\mathcal{F}_{\mathsf{Ident}}$.
   - If $\mathcal{F}_{\mathsf{Ident}}$ returns cheating servers $\mathcal{J}$
     signs and sends $(\textsc{Call}, sid, (\mathsf{cn}_{\mathsf{Lock}}, f(\textsc{Abort}), \{0, \bar{\mathbf{0}}\}_{j\in[m]}), \bar{\mathbf{0}}), \mathsf{vk})$ to $\mathcal{F}_{\mathsf{Ledger}}$.
   - Else server P_i obtains $\{y_j^{(i)}, \bar{\mathbf{w}}_j^{(i)}\}_{j\in[m]}$ from **Reveal**, signs and
     sends $(\textsc{Call}, sid, (\mathsf{cn}_{\mathsf{Lock}}, f(\textsc{Abort}), \{y_j^{(i)}, \bar{\mathbf{w}}_j^{(i)}\}_{j\in[m]}), \bar{\mathbf{0}}), \mathsf{vk})$ to $\mathcal{F}_{\mathsf{Ledger}}$
3. Updates $\mathcal{F}_{\mathsf{Clock}}$ and *terminates*.

Fig. 13: Part 2 - Protocol $\Pi_{\underline{\mathsf{C}}\mathsf{Contract}}$ UC-securely realizing $\mathcal{F}_{\underline{\mathsf{C}}\mathsf{Contract}}$.

Program $\mathcal{X}_{\mathsf{Lock}}$, extends $\mathcal{X}_{\underline{\mathsf{C}}\mathsf{Ledger}}$

On input $(\nu \,|\, \gamma \,|\, \bar{\mathbf{w}} \,|\, \mathsf{cn}, \mathsf{fn}, x, \bar{\mathbf{v}}, \mathsf{vk})$, $\mathcal{X}_{\mathsf{Lock}}$ parses γ as $(\mathcal{L}_{\mathsf{Conf}}, \mathcal{L}_{\mathsf{Lock}}, \mathcal{M}, \mathcal{J}, \mathsf{st})$, where $\mathcal{L}_{\mathsf{Lock}}$ is a ledger of locked coins, $\mathcal{M}$ is a map of account verification keys to coin commitment masks, $\mathcal{J}$ is set of cheating servers and $\mathsf{st} \in \{\texttt{enroll}, \texttt{enrolled}, \texttt{lock}\}$ captures the phase the confidential coin lock is currently in.

Init lock: parse x as $\mathsf{vk}_{\mathsf{TSig}}$, set state to `enroll`.

Enroll: parse x as $(c, \hat{c}) \in \mathbb{G}^{\mathsf{com}} \times \mathbb{G}^{\mathsf{com}}$.
1. Assert state is `enroll` and $c \in \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}]$. Set $\mathcal{L}_{\mathsf{Lock}}[\mathsf{vk}] \leftarrow \mathcal{L}_{\mathsf{Lock}}[\mathsf{vk}] \cup \{c\}$, $\mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}] \leftarrow \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}] \setminus \{c\}$ and $\mathcal{M}[\mathsf{vk}] \leftarrow \hat{c}$.
2. If round ν has progressed since last state transition to `enroll`, set st to `enrolled`. Return updated $(\mathcal{L}, \gamma' = (\mathcal{L}_{\mathsf{Conf}}, \mathcal{L}_{\mathsf{Lock}}, \mathcal{M}, \mathcal{J}, \mathsf{st}), \bar{\mathbf{w}})$.

Evaluated: parse x as $\sigma_{\mathsf{vk}_{\mathsf{TSig}}}(\mathsf{eval}) \in \{0,1\}^*$.
1. Assert state st is `enrolled`, verify $\sigma_{\mathsf{vk}_{\mathsf{TSig}}}(\mathsf{eval})$ via $\mathcal{F}_{\mathsf{TSig}}$.
2. If no *abort* is returned and two $\mathcal{F}_{\mathsf{Clock}}$ rounds (observed via ν) have progressed since last state transition to `enrolled`: set st to `lock`.
3. Return updated $(\mathcal{L}, \gamma' = (\mathcal{L}_{\mathsf{Conf}}, \mathcal{L}_{\mathsf{Lock}}, \mathcal{M}, \mathcal{J}, \mathsf{st}), \bar{\mathbf{w}})$.

Settle: parse x as $\sigma_{\mathsf{vk}_{\mathsf{Lock}}}(\{y_j, \bar{\mathbf{v}}_j\}_{j\in[m]})$.
1. Assert state is `lock`, verify $\sigma_{\mathsf{vk}_{\mathsf{Lock}}}(\{y_j, \bar{\mathbf{v}}_j\}_{j\in[m]})$ via $\mathcal{F}_{\mathsf{TSig}}$.
2. If no *abort* is returned and $\mathcal{F}_{\mathsf{Clock}}$ round has progressed, run $\texttt{payout}(\{\bar{\mathbf{v}}_j\}_{j\in[m]})$.

Abort: parse x as $\{y_j^{(i)}, \bar{\mathbf{v}}_j^{(i)}\}_{j\in[m]}$.
1. If state is `enroll` or `enrolled`, run `reimburse`.
2. Else if state is `lock`,
   - Send (TEST-REVEAL, *sid*) and (VERIFY, *sid*, $\{y_j^{(i)}, \bar{\mathbf{v}}_j^{(i)}\}_{j\in[m]}$) to $\mathcal{F}_{\mathsf{Ident}}$.
   - If no *abort* is returned and $\mathcal{F}_{\mathsf{Clock}}$ round has progressed, reconstruct $\{\bar{\mathbf{v}}_j\}_{j\in[m]}$ when all shares received from $\mathcal{P}$ and run $\texttt{payout}(\{\bar{\mathbf{v}}_j\}_{j\in[m]})$.
   - Else if *abort* is returned from $\mathcal{F}_{\mathsf{Ident}}$ or shares are missing, record cheating servers $\mathcal{J}$ and run $\texttt{reimburse}(\mathcal{J})$.

$\texttt{payout}(\{\bar{\mathbf{v}}_j\}_{j\in[m]})$: for each C_j's output $\bar{\mathbf{v}}_j \in \{\bar{\mathbf{v}}_j\}_{j\in[m]}$,
1. $\mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}_j] \leftarrow \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}_j] \cup \{c_j \cdot \hat{c}_j^{-1}\}$, where $c_j = \mathbf{g}^{\bar{\mathbf{v}}_j} h^0$, $\hat{c}_j = \mathcal{M}[\mathsf{vk}_j]$. $\mathcal{L}_{\mathsf{Lock}} \leftarrow \emptyset$, $\mathcal{M} \leftarrow \emptyset$. Return updated $(\mathcal{L}, \gamma' = (\mathcal{L}_{\mathsf{Conf}}, \mathcal{L}_{\mathsf{Lock}}, \mathcal{M}, \mathcal{J}, \texttt{enroll}), \bar{\mathbf{w}})$.

$\texttt{reimburse}(\mathcal{J})$: for $\mathsf{vk} \in \mathsf{dom}(\mathcal{L}_{\mathsf{Lock}})$,
1. Set $\mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}] \leftarrow \mathcal{L}_{\mathsf{Conf}}[\mathsf{vk}] \cup \mathcal{L}_{\mathsf{Lock}}[\mathsf{vk}]$.
2. Set $\mathcal{L}_{\mathsf{Lock}} \leftarrow \emptyset$, $\mathcal{M} \leftarrow \emptyset$. Return updated $(\mathcal{L}, \gamma' = (\mathcal{L}_{\mathsf{Conf}}, \mathcal{L}_{\mathsf{Lock}}, \mathcal{M}, \mathcal{J}, \texttt{enroll}), \bar{\mathbf{w}})$.

Fig. 14: The smart contract code $\mathcal{X}_{\mathsf{Lock}}$ for extended confidential token functionality.

Program $\mathcal{X}_{\mathsf{Collateral}}$

Parameterized by signature verification keys $\{\mathsf{vk}_1, ..., \mathsf{vk}_n\}$ associated with servers $\mathcal{P} = \{P_1, ..., P_n\}$, contract identifier $\mathtt{cn}_{\mathsf{Lock}}$ and collateral threshold $\bar{\mathbf{v}}_{\mathsf{coll}}$.

Deposit collateral:

1. Assert local state is `deposit`, $\mathtt{cn}_{\mathsf{Lock}}$ state is `enroll`, and $\bar{\mathbf{v}}_{\mathsf{in}} \geq \bar{\mathbf{v}}_{\mathsf{coll}}$.
2. If collateral received by accounts associated with vk for $i \in [n]$, set state to `coll`.

Round activation: If $\mathcal{F}_{\mathsf{Clock}}$ round has progressed since update to `coll`.

1. If $\mathtt{cn}_{\mathsf{Lock}}$ is in `deposit`, return collateral and set state to `deposit`.
2. Else if $\mathtt{cn}_{\mathsf{Lock}}$ is in `abort` with cheating $\mathcal{J} \subseteq \mathcal{P}$, distribute $\mathcal{J}$'s collateral to $\mathcal{C}'$. Return collateral of honest servers. Set state to `deposit`.

Fig. 15: The smart contract code $\mathcal{X}_{\mathsf{Collateral}}$.