GECO: A Confidentiality-Preserving and High-Performance Permissioned Blockchain Framework for General Smart Contracts

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Abstract

Data confidentiality is essential for blockchain applications handling sensitive data. A promising approach to achieving confidentiality is using cryptographic primitives like homomorphic encryption to encrypt client data, and enforcing the correct execution of smart contracts through non-interactive zero-knowledge proofs (NIZKPs). However, existing solutions still face significant limitations in supporting general smart contracts. Firstly, these solutions cannot tolerate non-deterministic contracts whose correct execution cannot be directly proven by NIZKPs. Secondly, many of these solutions cannot support arbitrary arithmetic operations over ciphertext because they use operation-restricted cryptographic primitives such as partial homomorphic encryption.

We present GECO, a confidentiality-preserving and high-performance permissioned blockchain framework for general smart contracts. GECO supports non-deterministic contracts with general cryptographic primitives (e.g., fully homomorphic encryption), allowing arbitrary arithmetic operations. By co-designing with the multi-party trusted execution mechanism of execute-order-validate blockchains such as Hyperledger Fabric, GECO generates contract logic-agnostic NIZKPs, which prove only that quorum parties produce consistent results, thereby ensuring the contract execution correctness while addressing potential result non-determinism. For better performance, GECO merges multiple conflicting transactions into a single one, minimizing the occurrence of conflicting aborts and invocations of cryptographic primitives. Theoretical analysis and extensive evaluation on notable contracts demonstrate that GECO achieves strong confidentiality guarantee among existing systems and supports general smart contracts. Compared to four confidentiality-preserving blockchains, GECO achieved up to 7.14× higher effective throughput and the shortest 99% tail latency.

1 Introduction

Blockchains are widely favored in both industry and academia. The main spur is their support of smart contracts that enable trusted execution over a tamper-resistant ledger shared among mutually untrusted participants. However, notable blockchains like Ethereum [46] process and store client data in plaintext, raising deep concerns over data confidentiality. Such concerns are particularly problematic for applications involving highly sensitive information like medical data [26], as they are subject to stringent privacy laws, such as the General Data Protection Regulation of the European Union [45].

Much previous work has been proposed to achieve data confidentiality in smart contracts, and existing work can be summarized into two approaches. The first is the architecture approach, which designs dedicated blockchain architectures for data confidentiality. However, this approach imposes strong trust assumptions on either specific hardware or third-party smart contract executors. For example, Ekiden [12] uses trusted execution environments (TEE), while Arbitrum [27], Caper [2], and Qanaat [3] are vulnerable to malicious smart contract executors as these executors execute transactions over plaintexts and thus may disclose clients' sensitive data.

The second is the cryptography approach. It employs cryptographic primitives like homomorphic encryption (HE) to encrypt client data without extra trust assumptions and to mandate smart contracts to execute directly on ciphertexts [41–43], preventing sensitive data exposure to malicious participants. This approach uses non-interactive zero-knowledge proofs (NIZKPs) to ensure the correctness of results (in ciphertext), without leaking any plaintext involved. Specifically, existing work generates NIZKPs by a *re-execution method*, in which NIZKPs decrypt transaction inputs and results, then re-execute transactions using the decrypted inputs, and verify the consistency between the decrypted and re-executed results.

However, because of the re-execution method, the existing cryptography approaches still face two intrinsic limitations. Firstly, existing work is incompatible with non-deterministic contracts, which can enhance performance via non-deterministic language features like multithreading [36]. However, these contracts may produce inconsistent results under the same input and initial state in different executions, leading to incompatibility with NIZKPs generated by the re-

execution method, which implies that identical input will always produce the same result.

Secondly, existing work of the cryptography approach suffers from poor performance due to the re-execution method. This method is inefficient in NIZKP generation and verification, especially when integrated with general cryptographic primitives such as fully homomorphic encryption (FHE), which allows arbitrary arithmetic computations over ciphertexts. To illustrate, executing the BFV scheme [10, 19] (a popular FHE scheme) inside the elliptic curve-based NIZKP [14] takes tens of seconds to generate or verify one NIZKP [40]. Even when employing lightweight cryptographic primitives such as partial homomorphic encryption (PHE) which restricts arithmetic operations, the NIZKP operations remain cumbersome. For instance, generating a Groth16 [33] NIZKP using 2048-bit keys for the Paillier PHE scheme [34], consumes more than 256 GB of memory [41], which is impractical for commodity desktops available today.

Overall, we believe the re-execution method of existing cryptography approaches for generating NIZKPs is the root cause of their inability to support non-deterministic contracts and their poor end-to-end performance.

In this study, our key insight to address these limitations is that, *we can re-assign the responsibility for ensuring the correct execution of contracts between blockchains and cryptographic primitives.* Specifically, instead of relying solely on NIZKPs to prove the correct execution of contracts, we integrate NIZKPs with the quorum-based trusted execution mechanism of execute→order→validate (EOV) permissioned blockchains, such as Hyperledger Fabric (HLF) [4]. This mechanism first executes transactions on multiple executor nodes (Figure 1). The execution is considered correct if quorum nodes produce consistent results. EOV eliminates the result inconsistency caused by non-determinism, thereby enabling the support for non-deterministic contracts. By decoupling the correctness proving logic from the contract logic, EOV significantly reduces the correctness proving overhead for contracts involving expensive cryptographic primitives.

This insight leads to GECO[1], a confidentiality-preserving and high-performance permissioned blockchain framework for general smart contracts. A general smart contract can be non-deterministic (e.g., multi-threaded) and/or involve general cryptographic primitives such as FHE to support arbitrary arithmetic computations. GECO carries a novel Confidentiality-preserving Execute-Order-Validate (CEOV) workflow for provably correct execution of general smart contracts involving ciphertexts. CEOV executes transactions in three steps. Firstly, a client submits a transaction with plaintext input to a trusted manager, referred to as the *lead executor*. The lead executor employs a designated cryptographic primitive (e.g., a FHE scheme), as specified by the invoked contract, to encrypt the input. The lead executor belongs to

[1] GECO denotes GEneral COnfidentiality-preserving blockchain framework.

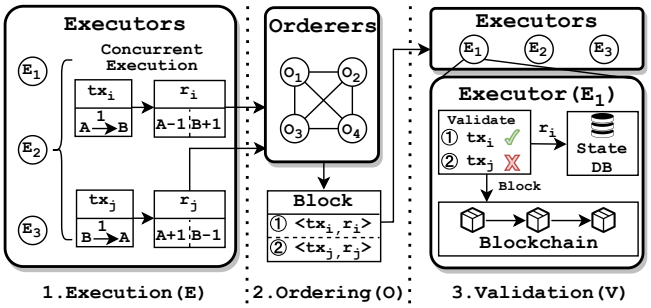


Figure 1: For high performance, EOV executors concurrently executes transactions tx_i and tx_j, causing conflicting aborts.

the client's organization, and consequently, GECO imposes no additional trust assumptions on the original trust model of EOV. Secondly, the lead executor dispatches the transaction to multiple executors, which independently and concurrently execute the transaction over ciphertexts. Thirdly, the lead executor generates NIZKPs to prove that quorum results are consistent, rather than re-executing the transaction inside NIZKPs as in existing re-execution method. By leveraging the CEOV workflow, GECO effectively preserves data confidentiality and ensures the execution correctness for general smart contracts.

However, GECO still faces a non-trivial performance challenge due to the transaction conflicting aborts of EOV. In particular, EOV concurrently executes all transactions for high performance and checks conflicts before committing transactions for data consistency (i.e., optimistic concurrency control [4]). As Figure 1 shows, when multiple transactions concurrently write to the same key-value pair in the blockchain state database, only one transaction can be successfully committed (e.g., tx_i); other conflicting transactions must be aborted (e.g., tx_j). This challenge is exacerbated in GECO due to the costly cryptographic primitives, which prolong the execution latency of transactions and thereby increase the chance of conflicting abort. For example, Microsoft SEAL [38], a highly optimized FHE library, takes 2822 milliseconds to execute a single FHE multiplication [32]. Thus, conflicting aborts cause serious performance degradation on executor nodes.

To tackle the challenge, we propose Correlated Transaction Merging (CTM), a new concurrency control protocol for cryptographic computations. CTM exploits the similarities among conflicting transactions to minimize conflicting aborts. Specifically, conflicting transactions invoking the same contract generally write to the same keys. By merging conflicting transactions into a single one, we can commit all transactions without abortion and preserve their original semantics. Consider a scenario where, for key X, two transactions attempt to perform $X+1$ and $X+2$ respectively. CTM merges and commits the transactions into a single transaction that performs $X+3$.

CTM consists of *offline analysis* and *online scheduling*. CTM's offline analysis determines whether multiple conflicting transactions invoking the contract can be merged into a single equivalent transaction. CTM's online scheduling tracks

the read-write sets of transactions within each block to identify and merge the mergeable transactions. CTM is especially suitable for contracts involving ciphertexts, as it effectively reduces the waste of computing resources caused by conflicting aborts and the invocations of costly cryptographic primitives.

We implemented GECO on HLF [4], a prominent EOV permissioned blockchain framework. We integrated GECO with Lattigo [32], a performant FHE library, and Gnark [13], a popular NIZKP library. We evaluated GECO using both the SmallBank workload [25] under different conflict ratios, and ten diverse blockchain applications, including both deterministic and non-deterministic contracts. We compared GECO with HLF and ZeeStar, a notable confidentiality-preserving blockchain system using the cryptography approach [41]. Our evaluation shows that:

- GECO is efficient (§6.1). GECO achieved up to 7.14× higher effective throughput and 14% lower end-to-end latency than ZeeStar. While GECO had 32% lower throughput compared to HLF, HLF does not preserve confidentiality.
- GECO is secure (§6.2). GECO can maintain high effective throughput and low end-to-end latency under attack from malicious participants.
- GECO is general (§6.3). GECO tolerates non-deterministic contracts and supports cryptographic primitives like FHE which allows arbitrary computations over ciphertexts.

Our main contributions are CEOV, a new confidentiality-preserving blockchain workflow tailored for general smart contracts, and CTM, a new concurrency control protocol for transactions involving ciphertexts. CEOV addresses the challenge of ensuring the provably correct execution of non-deterministic contracts employing general cryptographic primitives (e.g., FHE), rendering GECO more secure than existing cryptography-based confidentiality-preserving blockchains. CTM boosts the end-to-end performance by minimizing both the conflicting aborts of EOV blockchains and the high overhead of cryptographic primitives. Overall, GECO can benefit blockchain applications that desire both data confidentiality and high performance, such as supply chain [17] and healthcare [30]. GECO can also attract traditional non-deterministic applications developed in general programming languages like Go, to be deployed upon. GECO's code is available at https://github.com/osdi25geco/osdi25geco.

2 Background

2.1 EOV Permissioned Blockchain

A blockchain is a distributed ledger that records transactions across multiple nodes. It is either *permissionless* or *permissioned*. Permissionless blockchains (e.g., Ethereum [46]) are open to anyone, and their participants are mutually untrusted. In contrast, permissioned blockchains (e.g., HLF [4]) are maintained by a group of explicitly identified organizations, and only grant access to authenticated participants that are trusted within their organizations. Thanks to identity authentication, permissioned blockchains can utilize fast BFT consensus protocols like HotStuff [47] to tolerate malicious nodes.

Permissioned blockchains are divided into two types based on their workflows: *order→execute* (OE) and *execute→order→validate* (EOV). As Figure 2a shows, the OE workflow has two phases. Firstly, the orderers establish a global transaction order (**O**); Next, all executors execute the transactions in the predetermined order (**E**). As each executor executes all transactions independently, this workflow cannot tolerate non-deterministic transactions.

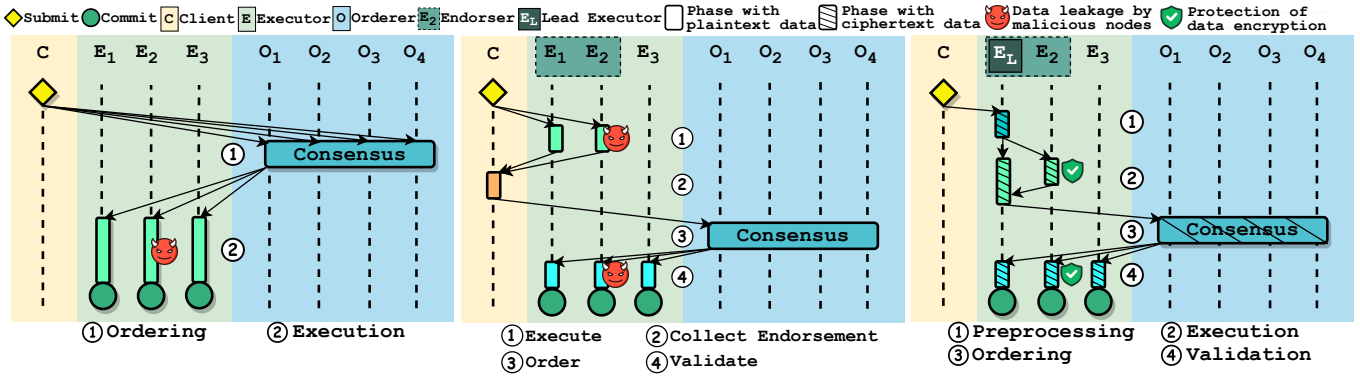
The EOV workflow (Figure 2b) incorporates a **quorum-based trusted execution mechanism** to achieve high performance and tolerate non-deterministic transactions. Specifically, the application designates a group of executors to execute each transaction. A transaction's execution is deemed correct *iff* a quorum of these executors produces consistent execution results for it. The EOV workflow consists of three key phases: execution, ordering, and validation.

Execution (E): A group of executors known as endorsers is selected to concurrently execute each transaction. During this execution, each endorser produces a read set and a write set. The read set includes the version of the keys in the database that the transaction has read, while the write set captures the new values that the transaction intends to write. The client then gathers the results from multiple endorsers to verify consistency. If the endorsers' results are consistent, the transaction execution is deemed correct, and the client forwards the transaction's execution results to the ordering service.

Ordering (O): The ordering service runs a consensus protocol (e.g., PBFT [11]) to determine the order of transactions within each block.

Validation (V): Once the order is determined, each executor independently validates the transactions through multi-version concurrency control (MVCC). During validation, the executor check if the keys' versions in the read set still match the current state of the database. If the read set values are unchanged, the transaction is considered valid and is applied to the database with its write set. However, if any version mismatch occurs, the transaction is aborted to prevent conflicts arising from concurrent modifications. This conflicting abort problem of EOV blockchains is particularly detrimental to the end-to-end performance, especially for smart contracts with intensive write conflicts, such as supply chain [36].

GECO leverages EOV's quorum-based trusted execution to avoid the computationally intensive NIZKP generation that is based on re-execution method, enabling support for general smart contracts while maintaining high performance. Moreover, GECO proposes CTM to minimize the conflicting aborts via merging conflicting transactions, thereby further enhancing the performance.



(a) Order-Execute (b) Execute-Order-Validate (c) Confidentiality-preserving Execute-Order-Validate

Figure 2: Our CEOV workflow (Figure 2c) and two existing typical permissioned blockchain workflows.

2.2 Homomorphic Encryption

GECO encrypts sensitive client data using homomorphic encryption (HE), which allows direct computation over ciphertexts without decryption. An HE scheme has four algorithms: *KeyGen* generates key pairs used by other operations; *Enc(m, pk, r)* uses the public key pk to encrypt a plaintext m into a ciphertext c with randomness r; *Dec(c, sk)* uses the private key sk to decrypt ciphertext c back to the original plaintext m; $\oplus$ is a binary operator taking two ciphertexts as input and produces a result ciphertext. For instance, in an additive HE scheme, the $\oplus$ operator satisfies the following property:

$$Enc(m_1, pk, r_1) \oplus Enc(m_2, pk, r_2) = Enc(m_1 + m_2, pk, r_3)$$

for some randomness r_3. HE schemes are classified into two main types based on the supported operators: partial homomorphic encryption (PHE) and fully homomorphic encryption (FHE). Although PHE schemes have relatively low computation overhead, they are limited to only one type of arithmetic operation, either addition or multiplication. This restriction compromises the generality of smart contracts, as discussed in §1. In contrast, FHE schemes are more computation-intensive but allow for arbitrary combinations of these operations. This flexibility arises because, once both addition and multiplication are supported, any computation can be expressed as a combination of these two operations. Furthermore, substantial improvements have been made to improve the performance of FHE schemes since the proposal of the first plausible FHE scheme [21], making FHE a promising and practical solution for supporting general smart contracts.

In this study, we use FHE to support general computations. Specifically, GECO encrypt clients' data with FHE schemes, thereby allowing GECO executors to perform both addition and multiplication directly over ciphertexts without disclosing their corresponding plaintexts during contract execution.

2.3 Non-Interactive Zero-Knowledge Proofs

GECO co-designs the non-interactive zero-knowledge proof (NIZKP) [20, 23] with the EOV workflow to ensure the correctness of transaction execution. NIZKP is a cryptographic primitive that enables a prover P to prove knowledge of a private input s to a verifier V without revealing s. Once P generates a NIZKP using a *proving key*, V can verify the proof using the respective *verifying key* without P being present. Formally, given a proof circuit ϕ, a private input s, and a public input x, the prover P can generate a NIZKP to prove knowledge of s satisfying the predicate $\phi(s;x)$. A popular type of NIZKP is zero-knowledge succinct non-interactive arguments of knowledge (zkSNARK) [8, 24], which allows any arithmetic circuit ϕ and guarantees constant-cost proof verification in the size of ϕ, making it suitable for blockchain applications [5, 15, 42]. GECO uses the Gnark [13] implementation of the Groth16 [33] system (a zkSNARKs construction) with advantages including constant proof size (several kilobytes) and short verification time (tens of milliseconds).

System	Data Encryption	Multiple Parties	General Contract	High Performance
✧ Ekiden [12]	✓	✓	✗	✓
✧ Arbitrum [27]	✗	✓	✗	✓
✧ Qanaat [3]	✗	✓	✓	✓
✧ Caper [2]	✗	✓	✓	✓
♦ ZeeStar [41]	✓	✤	✗	✗
♦ Zapper [43]	✓	✗	✗	✗
♦ Hawk [29]	✓	✓	✗	✓
♦ SmartFHE [40]	✓	✓	✗	✗
♦ FabZK [28]	✓	✗	✗	✗
♦ GECO	✓	✓	✓	✓

Table 1: Comparison of GECO and related confidentiality-preserving blockchains. "✧ / ♦" means that the system either takes the architecture approach (✧) or the cryptography approach (♦). "✤" means that ZeeStar supports only addition but not multiplication over ciphertexts of different parties.

2.4 Related Work

We now discuss previous work on confidentiality-preserving blockchains, as illustrated in Table 1.

Architecture approach. Existing work attempts to ensure data confidentiality by adopting dedicated blockchain architectures without using cryptography technology. Ekiden [12]

demands TEE hardware to process private data. Arbitrum [27] imposes strong trust assumptions on smart contract executors that might be incentivized to disclose clients' sensitive data. Caper [2] and Qanaat [3] adopt dedicated data models that limits data access to authenticated parties but still exposes one organization's data to other organizations.

Cryptography approach. Existing work of the cryptography approach uses HE to protect data confidentiality and NIZKP to enforce the execution correctness of smart contracts. However, existing work does not support general smart contracts.

ZeeStar [41] uses an additive PHE scheme [31] and supports ciphertext multiplication by repeating additions. However, such multiplication is inefficient and cannot accept foreign values (i.e., ciphertexts encrypted by different parties). Zapper [43] uses an oblivious Merkle tree construction and a NIZK processor for data confidentiality. Neither ZeeStar nor Zapper tolerate non-deterministic contracts due to their reliance on the OE workflow, as discussed in §2.1.

Hawk [29] uses symmetric encryption for data confidentiality and NIZKP for execution correctness of smart contracts. However, Hawk is dedicated only to money transfer applications and does not support general smart contracts.

SmartFHE [40] is Ethereum-based and uses FHE schemes. It cannot tolerate non-deterministic contracts since it relies on the OE workflow. It does not support contracts involving foreign values as this requires a multi-key variant of SmartFHE that is currently impractical as per the authors.

FabZK [28] adopts a specialized tabular ledger data structure to obfuscate the involved organizations. However, this data structure severely restricts the compatible blockchain applications, making FabZK unable to support general contracts.

3 Overview

3.1 System Model

Same as existing EOV permissioned blockchains, GECO has three types of participants: *client*, *orderer*, and *executor*. The latter two are referred to as *nodes*. GECO groups participants into *organizations*. Each organization runs multiple executors and orderers, and possesses a set of clients. We describe the functionalities of each participant type as follows:

Clients. Only clients can submit transactions to nodes for execution and commitment.

Orderers. GECO orderers determine the order of transactions in blocks via a consensus protocol (e.g., PBFT [11]).

Executors. Each executor is responsible for three tasks: executing transactions, validating results, and maintaining a local blockchain state database. As Figure 3 shows, each organization has a designated *lead executor*, which is built upon the existing Fabric Gateway [16] with the following extra tasks:

- Detect and merge multiple conflicting transactions.
- Encrypt transaction inputs with the cryptographic primitive specified by the invoking smart contract.

No.	API	Description
	LEAD EXECUTOR APIS	
1	`Preprocess(tx)`	Preprocess the given transaction (§4.2)
2	`Prove(rs)`	Generate NIZKPs (§4.2) to prove that quorum results are consistent.
3	`Verify(rs,nizkps)`	Verify NIZKPs (§4.2) to ensure that quorum results are consistent.
	SMART CONTRACT APIS	
4	`Analyze(C)`	Run the offline analysis (§4.1) on the contract.
5	`Require(predicate)`	Abort transaction if the predicate is false. (§4.2)

Table 2: libGECO APIs.

- Dispatch transactions to other executors and orderers for execution and ordering, respectively.
- Generate NIZKPs to prove the correctness of execution by checking the consistency of transaction results.

Threat model. GECO adopts the Byzantine failure model [6, 11], where orderers run a BFT consensus protocol that tolerates up to $\lfloor \frac{N-1}{3} \rfloor$ malicious orderers out of N orderers. GECO participants trust all participants within the same organization but no participants from other organizations. Note that GECO inherits the same threat model of existing EOV permissioned blockchains [4, 35, 36] and does not require extra trust assumptions. We make standard assumptions on cryptographic primitives, including FHE and NIZKP.

GECO's guarantees. GECO's *confidentiality* guarantee ensures that all client data are stored and processed in ciphertext, and the corresponding plaintext can be only decrypted by participants from the client's organization. GECO's *generality* guarantee ensures that GECO supports the provably correct execution of smart contracts that are non-deterministic and/or involve any cryptographic primitives such as FHE to support general computations.

3.2 libGECO

GECO provides a library named libGECO with five APIs (see Table 2). The lead executor APIs assist lead executors in preprocessing transactions and ensuring the execution correctness. The smart contract APIs enable contract developers to analyze the mergeability (Definition 4.2) of the contract and enforce the validity of the given predicates involving ciphertexts. Note that the `Require()` API follows the idea of the *require* statement of ZeeStar [41]. We will further discuss how to integrate libGECO into GECO's protocol in §3.4 and §4.2.

3.3 Example Smart Contract

Listing 1 is the pseudocode of a token transfer contract, which confidentially transfers `val` tokens from the sender client `src` to the receiver client `dst`. Table 3 introduces the data types and functions used in Listing 1. Note that function `Add` and `Sub` can be implemented with any FHE scheme, such as the BFV scheme [10, 19]. In this contract, the `Require()` API (Table 2) verifies a NIZKP that decrypts the ciphertexts involved (i.e., `srcBalance` and `val`) and checks the predicate

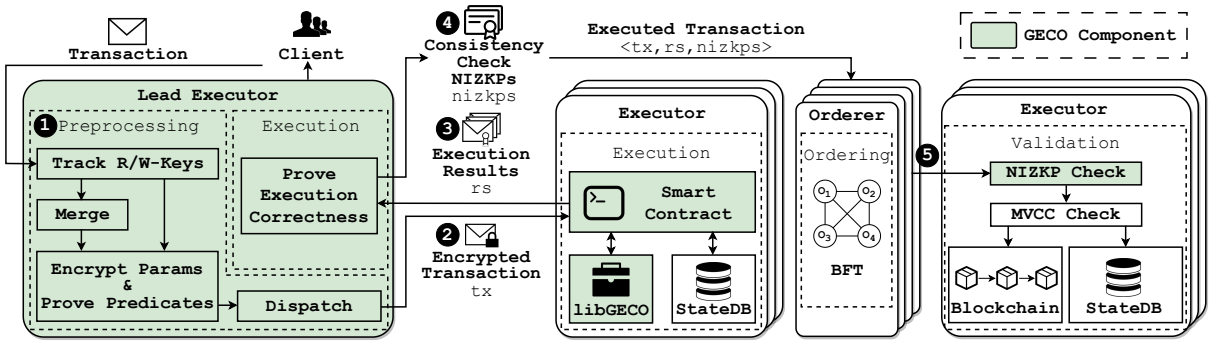


Figure 3: GECO's runtime workflow. GECO components are highlighted in green.

Data type	Description
`id`	Represent a unique identifier for a client.
`euint`	Represent an unsigned integer plaintext data, storing different ciphertexts encrypted for different clients.
Function	**Description**
`HasID(id)`	Check the existence of the given client `id`
`GetID()`	Get the `id` of the client that submits the transaction.
`GetState(key)`	Read a key-value pair from the state database.
`PutState(key,val)`	Write a key-value pair to the state database.
`Add(ct1,ct2)`	Perform FHE addition on the given ciphertexts.
`Sub(ct1,ct2)`	Perform FHE subtraction on the given ciphertexts.

Table 3: Data types and functions used in Listing 1.

with the plaintexts.. This NIZKP is generated by the lead executor in the preprocessing phase (§4.2) and is attached to the transaction. Intuitively, this contract ensures that each client's balance is kept confidential and only accessible to the respective client, while the number of tokens being transferred is known solely to the sender and the receiver.

```
func Transfer(id src, id dst, euint val) {
  if (!HasID(src) or !HasID(dst)) {Abort();}
  if (src != GetID()) {Abort();}
  euint srcBalance = GetState(src);
  Require(srcBalance >= val);       // Invoke API 5
  euint dstBalance = GetState(dst);
  PutState(src, Sub(srcBalance, val));
  PutState(dst, Add(dstBalance, val));
}
```

Listing 1: An example contract for confidential token transfer. We denote a transaction (invoking the contract) that transfers *val* tokens from account A to B as $A \xrightarrow{val} B$.

3.4 GECO's Protocol Overview

GECO has two sub-protocols: (1) *offline contract analysis* and (2) *runtime transaction schedule*.

Offline contract analysis (§4.1). Before contract deployment, the developer invokes the `Analyze()` API on the contract. This API performs the offline analysis of GECO's CTM protocol to determine whether the contract is *mergeable* (Definition 4.2). For example, the contract in Listing 1 is *additively mergeable*: multiple conflicting transactions invoking this contract with identical `src` and `dst` ($tx_1 : A \xrightarrow{1} B$ and $tx_2 : A \xrightarrow{1} B$) can be merged into one transaction ($tx_{1,2} : A \xrightarrow{2} B$) by summing their `val`, while keeping `src` and `dst` unchanged.

Runtime transaction schedule (§4.2). GECO incorporates a new CEOV workflow and the CTM protocol to schedule transaction executions at runtime, as shown in Figure 3.

Phase 1: Preprocessing. The lead executor invokes the `Preprocess()` API to preprocess the transactions submitted by clients. Firstly, the lead executor invokes the CTM protocol to merge transactions (❶ in Figure 3): it caches transactions submitted by clients from the same organization (§3.1), merges mergeable conflicting transactions, and leaves others unchanged. Next, the lead executor encrypts all transaction's plaintext inputs of data type `euint` using the encryption keys of respective organizations. In addition, for contracts using the `Require()` API, the lead executor generates NIZKPs to prove the predicates. Lastly, the lead executor selects a group of executors, known as *endorsers* in EOV [4], and dispatches the encrypted transactions to the endorsers for execution.

Phase 2: Execution. Upon receiving a transaction from a lead executor (❷), an endorser executes the invoked contract and produces a *read-write set* as the execution result. The endorser then sends the result back to the lead executor. After receiving results from all endorsers (❸), the lead executors invoke the `Prove()` API to generate NIZKPs, proving that quorum executors (i.e., a majority of executors) have produced consistent results, thereby ensuring execution correctness.

Phase 3: Ordering. The lead executors deliver the transactions with the NIZKPs to the orderers for transaction ordering (❹). The orderers run a BFT protocol to achieve consensus on the intra-block order of transactions and disseminate the block to all executors for validation and commitment.

Phase 4: Validation. When receiving a block from orderers (❺), the executor sequentially validates each transaction within the block in the predetermined order. Specifically, the executor invokes the `Verify()` API for each transaction to check the consistency of the transaction's quorum results. The executor commits only those transactions that do not conflict with previously committed transactions.

The highlights of GECO stem from achieving data confidentiality and high performance for general smart contracts by integrating the EOV workflow with cryptography primitives, combining the best of both worlds while addressing

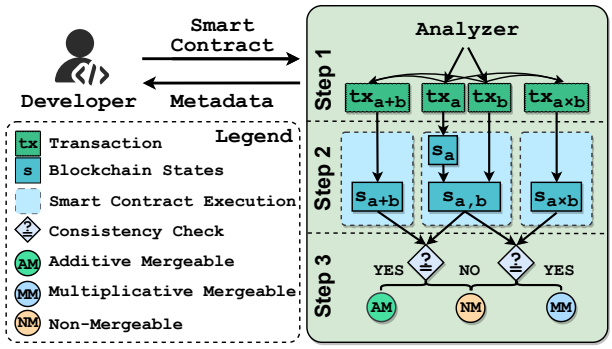


Figure 4: GECO's offline smart contract analysis protocol. tx_{a+b} and $tx_{a\times b}$ are formed by merging tx_a and tx_b via adding or multiplying their input parameters (§4.1). s_{a+b} and $s_{a\times b}$ are the states produced by executing tx_{a+b} and $tx_{a\times b}$. $s_{a,b}$ is the state produced by sequentially executing tx_a and tx_b.

their respective limitations. We illustrate this in two aspects. Firstly, GECO co-designs cryptographic primitives and the EOV workflow to address the fundamental limitations faced by existing cryptography-based confidentiality-preserving blockchains in supporting general contracts. Specifically, GECO's CEOV workflow leverages the quorum-based trusted execution of EOV permissioned blockchains to generate lightweight NIZKPs, which are agnostic to the contract logic and only serve to prove the consistency of quorum results, enabling the support for non-deterministic contracts. This also enables GECO to encrypt client data using cryptographic primitives that can perform arbitrary arithmetic computations over ciphertexts, such as FHE.

Secondly, GECO's CTM protocol simultaneously minimizes the invocations of costly cryptographic primitives and EOV's conflicting aborts by merging conflicting transactions without changing the original semantics.

4 Protocol Description

4.1 Offline Contract Analysis

Definition 4.1 (Smart contract parameter type)**.** Smart contract input parameters are classified into two types: *key* and *value*. The key parameters specify the contract's accessed keys while the value parameters derive the respective values.

Definition 4.2 (Mergeable smart contract)**.** A smart contract is *mergeable* iff, for any two conflicting transactions tx_1 and tx_2 that invoke the contract with identical key parameters, the transactions can be merged into a single transaction $tx_{1,2}$, whose key parameters are the same as tx_1 and tx_2, while the value parameters are the sums or products of the respective value parameters of tx_1 and tx_2.

A smart contract is *additive mergeable* iff it is mergeable and generates new value parameters by adding the respective value parameters of the conflicting transactions. Likewise, a smart contract is *multiplicative mergeable* iff it is mergeable and generates new value parameters by multiplying the respective value parameters of the conflicting transactions. Otherwise, the contract is *non-mergeable*.

Function	Description
`GetAllCFPs(C)`	Get all control flow paths of the contract.
`GenRandStateDB(C,p)`	Randomly generate a state database for the given contract and control flow path.
`GenRandParams(C,p)`	Randomly generate transaction parameters for the contract and control flow path.
`GenTX(k,v)`	Generate a transaction with the parameters generated by `GenRandParams()`.
`ExecTX(tx,state)`	Execute a transaction over a state database and return the updated state database.
`GetSize(paths)`	Get the number of control flow paths.
Variable	**Description**
`C`	The smart contract to be analyzed.
s, s_a, $s_{a,b}$, s_{a+b}, $s_{a\times b}$	States in blockchain database.
tx_a, tx_b, tx_{a+b}, $tx_{a\times b}$	Transactions.
`paths`	The set of all control flow paths.
`p`	A control flow path.
n_{a+b}	The counter for tracking $s_{a,b} = s_{a+b}$.
$n_{a\times b}$	The counter for tracking $s_{a,b} = s_{a\times b}$.
`k`	Key parameters for the smart contract.
v_a, v_b	Value parameters for the smart contract.

Table 4: Functions and variables for Algorithm 1.

The *offline analysis* determines whether a contract is additive mergeable, multiplicative mergeable, or non-mergeable. The offline analysis outputs a *metadata*, indicating the mergeability of the contract. During runtime, lead executors inspect the metadata and carry out transaction merging solely on additive mergeable and multiplicative mergeable contracts.

The `Analyze()` API implements the offline analysis protocol in three steps using random interpretation [1] (see Figure 4, Algorithm 1, and Table 4). Random interpretation generates different inputs and initial blockchain states to capture all possible control flow paths. By checking the consistency of the resulting states, random interpretation guarantees to identify contracts for which conflicting transactions sharing identical key parameters consistently produce identical resulting states regardless of the execution order. This consistency indicates the mergeability of the contract.

Analysis step 1: Preparation. For a contract C, the GECO analyzer first checks whether each parameter is a key or value parameter. Specifically, the analyzer checks all calls to EOV's state access APIs, such as `GetState()` and `PutState()` (see Table 3). A parameter is a key parameter if it is used as a key in any of these APIs; otherwise, it is a value parameter.

Next, for each control flow path, the analyzer randomly generates an initial blockchain state S, as well as two conflicting transactions tx_a and tx_b that share identical key parameters. In addition, the analyzer attempts to generate two "*merged*" transactions, namely tx_{a+b} and $tx_{a\times b}$, based on tx_a and tx_b. For tx_{a+b}, the analyzer generates new value parameters that are sums of the respective value parameters of tx_a and tx_b, while leaving the key parameters unchanged. Similarly, for

Algorithm 1: Offline analysis protocol (§4.1; API 4)

```
1  n_{a+b} ← 0; n_{a×b} ← 0; paths ← GetAllCFPs(C);
2  foreach p_1 in paths do
3      foreach p_2 in paths do
           // Step 1: Preparation
4          s ← GenRandStateDB(C);
5          k ←;
6          k, v_a, v_b ← GenRandParams(C, p);
7          tx_a ← GenTX(k, v_a); tx_b ← GenTX(k, v_b);
8          tx_{a+b} ← GenTX(k, v_a + v_b);
             tx_{a×b} ← GenTX(k, v_a × v_b);
           // Step 2: Execution
9          s_a ← ExecTX(tx_a, s); s_{a,b} ← ExecTX(tx_b, s_a);
10         s_{a+b} ← ExecTX(tx_{a+b}, s);
             s_{a×b} ← ExecTX(tx_{a×b}, s);
           // Step 3: Consistency check
11         if s_{a,b} = s_{a+b} then
12             n_{a+b} ← n_{a+b} + 1;
13         else if s_{a,b} = s_{a×b} then
14             n_{a×b} ← n_{a×b} + 1;
15 if n_{a+b} = GetSize(paths) then
16     return AdditiveMergeable
17 else if n_{a×b} = GetSize(paths) then
18     return MultiplicativeMergeable
19 else
20     return NonMergeable
```

$tx_{a\times b}$, the analyzer generates new value parameters that are products of the respective value parameters of tx_a and tx_b.

Analysis step 2: Random interpretation. GECO performs three independent runs of execution for C on the same initial state. In the first run, GECO executes tx_a and produces s_a. Subsequently, GECO executes tx_b on s_a, resulting in the final state $s_{a,b}$. In the second and third runs, GECO separately executes tx_{a+b} and $tx_{a\times b}$, producing s_{a+b} and $s_{a\times b}$, respectively.

Analysis step 3: Consistency check. Lastly, GECO conducts a consistency check among the three resulting states. If the equality $s_{a,b} = s_{a+b}$ holds for all control flow paths, the smart contract C is additive mergeable. Similarly, if $s_{a,b} = s_{a\times b}$, C is multiplicative mergeable. Otherwise, C is non-mergeable.

Assumptions and guarantees: An analyzable contract must satisfy two requirements. For analysis step 1, the read-write set should be identified in EOV's state access APIs before execution. For analysis step 2, the contract should not contain recursive contract calls [1]. GECO can easily integrate more advanced analysis techniques to relax requirements on contracts.

For non-analyzable contracts that do not satisfy these requirements, GECO conservatively regards these contracts as *non-mergeable*. Therefore, the non-analyzable contracts can at most degrade GECO's performance.

Based on these assumptions, GECO is guaranteed to maximize the performance of analyzable contracts while preserving the original semantics of all types of contracts, regardless of whether they are analyzable or not.

4.2 Runtime Transaction Schedule

GECO's *runtime protocol* (Algorithm 2 and Table 5) incorporates our new CEOV workflow to execute transactions in four phases, and enhances the performance with a CTM protocol.

Function	Description
`GetRWKeys(tx)`	Get all read and write keys of a transaction.
`DetectConflict(K,Q)`	Return the set of mergeable transactions and the set of non-mergeable transactions.
`Merge(txs)`	Merge the given set of mergeable transactions.
`Encrypt(txs,K)`	Encrypt the parameters of the transactions.
`ProvePredicates(txs)`	Generate NIZKPs to prove predicates if the transaction invokes the `Require()` API.
`Dispatch(txs)`	Dispatch the given transactions to endorsers.
`Execute(tx)`	Execute the transaction and return the result.
`ReplyResult(tx,r)`	Send the results to the lead executor.
`Order(tx,rs,nizkps)`	Send the transaction for ordering.
`CheckMVCC(rs)`	Perform a multi-version concurrency control check on the execution results.
`Commit(tx,rs,nizkps)`	Commit the given transaction.
`AppendBlock(blk)`	Append the given block to the local copy of the blockchain.
Variable	**Description**
`K`	All read and write keys for transactions in `Q`.
`Q`	The transaction buffering queue.
`T`	The threshold number of transactions in `Q`.
$\texttt{txs}_\texttt{m}$	The set of mergeable transactions.
$\texttt{txs}_\texttt{n}$	The set of non-mergeable transactions.
$\texttt{txs}_\texttt{e}$	The set of encrypted transactions.

Table 5: Functions and variables for Algorithm 2.

Phase 1: Preprocessing. The lead executor invokes the `Preprocess()` API to merge and encrypt client transactions.

Phase 1.1: Tracking read and write keys. For each block, the lead executor buffers the transactions in a queue and keeps track of each transaction's read and write keys. For example, for a transaction $(tx : A \xrightarrow{val} B)$ that invokes the contract in Listing 1, the lead executor tracks that the transaction has two read keys (A and B) and two write keys (A and B).

When a timeout occurs or the number of queuing transactions exceeds a threshold, the lead executor detects conflicting transactions according to their read and write keys. Next, the lead executor runs our CTM protocol (Phase 1.2) to merge conflicting transactions with identical key parameters and encrypts all transactions using FHE (Phase 1.3).

Phase 1.2: Correlated transaction merging (GECO's CTM protocol). For conflicting transactions with identical key parameters, the lead executor merges them by preserving their key parameters and generating new value parameters. In particular, the lead executor generates new value parameters by adding or multiplying the original value parameters of the mergeable transactions that invoke either an additive mergeable or multiplicative mergeable contract, respectively.

Phase 1.3: Encrypting transaction parameters and proving predicates. The lead executor encrypts the transaction input parameters that are of data type `euint`, namely encrypted unsigned integers (see Table 3). The lead executor analyzes the read and write keys associated with the `euint` parameters, then encrypts the parameter plaintexts using the encryption keys of the clients specified by the read and write keys. For example, for transaction $tx : A \xrightarrow{val} B$ (Listing 1), as `val` is computed together with `srcBalance` and `dstBalance`, the

Algorithm 2: Runtime protocol of the lead executor (§4.2)

```
// Phase 1: Preprocessing (Invoke API 1)
K ← ∅; Q ← ∅;
Upon reception of Transaction tx from client; do
    K ← K ∪ GetRWKeys(tx);
    Q ← Q ∪ tx;
Upon timeout or |Q| ≥ T
    txs_m, txs_n ← DetectConflict(K, Q);
    txs_m ← Merge(txs_m);
    txs_e ← Encrypt(txs_m, K) ∪ Encrypt(txs_n, K);
    ProvePredicates(txs_e);
    Dispatch(txs_e);
// Phase 2: Execution
Upon reception of Transaction tx from lead executor; do
    r ← Execute(tx);
    ReplyResult(tx, r);
// Phase 3: Ordering
Upon reception of all Results rs for Transaction tx; do
    nizkps ← Prove(rs);                    // Invoke API 2
    Order(tx, rs, nizkps);
// Phase 4: Validation
Upon reception of Block blk; do
    For tx, rs, nizkps in blk; do
        if Verify(rs, nizkps) ∧            // Invoke API 3
          CheckMVCC(rs) then
            Commit(tx, rs, nizkps);
        AppendBlock(blk);
```

euint parameter val has two write keys A and B, which belongs to org_1 and org_2, respectively. Therefore, the lead executor generates two ciphertexts for val by encrypting val using org_1 and org_2's public keys, respectively.

The lead executor also generates NIZKPs for contracts that invoke the Require() API to validate specific predicates. For example, the contract in Listing 1 requires srcBalance to be not less than val for a successful token transfer. Thus, the lead executor generates a NIZKP which first decrypts the ciphertext (srcBalance) and then proves whether the predicate (srcBalance > val) holds. The NIZKPs are attached to the transactions for verification by other participants.

Phase 1.4: Dispatch. The lead executor disseminates transactions to the involved organizations' executors (known as "endorsers") for execution. For instance, the above tx is submitted to executors in org_1 and org_2 for executions.

Phase 2: Execution. The executors execute each transaction in two steps: (1) the endorsers produce execution results, and (2) the lead executor checks the correctness of executions.

Phase 2.1: Producing execution result. Upon receiving a transaction from a lead executor, the endorser invokes the contract specified by the transaction. The execution produces a read-write set as the result, which records the blockchain states that the transaction reads from and writes to the state database. Next, the endorser signs the result and replies it to the lead executor to check the execution correctness.

Phase 2.2: Checking the execution correctness. After collecting results from all endorsers, the lead executor ensures correct executions by proving that quorum endorsers produced consistent read-write sets. However, the read-write sets contain ciphertexts that cannot be directly compared as they involve random noise for security reasons [44]. To address this issue, the lead executor invokes the Prove() API to generate a *consistency check NIZKP* that first decrypts the ciphertexts belonging to clients of the same organization, and then checks the consistency of the plaintexts. Note that the consistency check NIZKP takes the decryption key as private input to protect the confidentiality of the decryption key. In the case where read-write sets contain ciphertexts of multiple organizations, the lead executors of those organizations all follow the same procedure for proving the result consistency.

For instance, consider a transaction tx that modifies three keys A, B and C, belonging to different organizations, namely org_1, org_2 and org_3. To prove the consistency of tx's results from different endorsers, org_1 provides a consistency check NIZKP that different endorsers produce consistent results for key A. Similarly, org_2 provides a NIZKP that different endorsers produce consistent results for key B. NIZKPs from org_1, org_2, and org_3 are all submitted for ordering, collectively forming the correctness proof of tx.

Note that a transaction's result is considered consistent iff the same quorum of endorsers produces consistent read-write set results for all keys. If the endorsers of org_1 and org_2 produce consistent results for key A, while the endorsers of org_2 and org_3 produce consistent results for key B, it indicates that the consistent results for different keys are produced by different quorums of endorsers. Consequently, we cannot affirm the consistency of tx's execution results.

Phase 3: Ordering. GECO orderers run a BFT consensus protocol (e.g., PBFT [11]) to reach a consensus on the transaction order within a block. After a block is agreed upon by all orderers, they distribute it to all executors for validation.

Phase 4: Validation. Upon receiving a block from orderers, the executor sequentially validates each transaction. This validation process involves two steps: (1) invoking the Verify() API to verify the consistency check NIZKPs associated with the transactions, and (2) performing a multi-version concurrency control (MVCC) check on the results. For each valid transaction, the executor commits the result to the blockchain state database. For invalid transactions, the executor does not commit their results (i.e., transaction abort). After the executor has validated all transactions, it permanently appends the block to its local copy of the blockchain.

4.3 Defend Against Malicious Participants

The above protocol ensures data confidentiality even in the presence of malicious participants. Specifically, each GECO participant can only access the plaintext data of clients within the same organization, as participants in the same organizations are mutually trusted (§3.1). For clients from other organizations, the participant can only access their ciphertext data but not the corresponding plaintexts.

While malicious participants cannot compromise GECO's

confidentiality, they can still significantly degrade its performance. In Phase 2.2, a lead executor may fail to submit the consistency check NIZKPs for specific transactions submitted by other organizations, either due to network failures or malicious intent, causing these transactions to be always aborted in Phase 4. The attack is detrimental in GECO because it causes a substantial waste of computation resources on multiple executors, especially when smart contracts involve resource-intensive FHE computations (§1).

To tackle the NIZKP omission attack, GECO mandates the lead executors to submit the *consistency check NIZKPs* for all transactions, even if the results from different executors are inconsistent. To reduce false positives caused by network failures, GECO executors track the number of NIZKP omissions for each lead executor. A lead executor is deemed malicious only when the number of omissions caused by the lead executor exceeds a configurable threshold (by default, ten omissions). GECO executors proactively reject transactions that involve organizations of malicious lead executors in Phase 1 for a long period (by default, 10000 blocks, after which the omission number for a lead executor is reset to zero), preventing the potential waste of computation resources.

5 Analysis

5.1 Correctness

Definition 5.1 (Correctness)**.** For any agreed block with a serial number s, assuming that all executors start with the same initial blockchain state, once all valid transactions in blocks with serial numbers $s' \leq s$ are committed, all benign executors will converge to the same state (BFT safety). This state equals to the state obtained by sequentially executing all valid transactions on the same initial state (ACID).

Proof. GECO achieves equivalent BFT safety to existing EOV blockchains [4] through two properties of consistency:

- *Block consistency*. GECO treats the consensus protocol as a blackbox, as illustrated in Phase 3 of the runtime protocol (§4.2). Thus, GECO inherits the mature consistency (safety) guarantee of existing BFT consensus protocols [7]. This ensures that all benign executors process and append the same blocks in the same order determined by the orderers.
- *State consistency*. Every benign executor follows the same deterministic protocol to validate and commit transactions, as demonstrated in Phase 4 of the runtime protocol (§4.2). A transaction's result is committed to the state database *iff* a quorum of the results is consistent and does not modify any key that has been modified by a previous transaction of the same block. This ensures that all benign executors maintain a consistent state and a consistent local copy of the blockchain.

GECO guarantees the ACID properties for transaction execution by inheriting them from the EOV workflow.

- *Atomicity*. GECO either commits or aborts each transaction.
- *Consistency*. GECO exclusively commits valid and consistent transaction results in a sequential order determined by the orderers. This leads to a consistent resulting state across benign executors given an identical initial state.
- *Isolation*. Each transaction operates independently, without interference or conflicts with other transactions.
- *Durability*. For a committed transaction, its changes to the blockchain state are permanent and irreversible. □

5.2 Liveness

Definition 5.2 (Liveness)**.** Any valid transaction tx submitted by a benign client in the ordering phase will eventually be included in a block by GECO.

Proof. GECO inherits the BFT liveness from existing EOV permissioned blockchains [4]. Specifically, the orderers run a BFT consensus protocol, which guarantees to finalize tx into a block B (§4.2) and deliver the block to all executors. □

5.3 Confidentiality

Definition 5.3 (Confidentiality)**.** For any transaction accessing the ciphertext data ct (with the corresponding plaintext data denoted as pt) belonging to a client of organization org, GECO guarantees that any attacker from a different organization $org*$ is unable to decrypt ct and obtain pt.

Proof. GECO's confidentiality guarantee is based on two inherent confidentiality guarantees separately provided by NIZKPs and the encryption scheme employed. Firstly, the private inputs for generating NIZKPs are impossible to be revealed by verifiers [23]. This enables GECO to ensure the confidentiality of NIZKPs' private inputs such as decryption keys (i.e., private keys), as discussed in §2.3 and §4.2. Secondly, the encryption scheme employed by GECO (e.g., the BFV scheme [10, 19]) achieves *indistinguishability under chosen-plaintext attack* (IND-CPA [9]), meaning that any attacker is computationally infeasible to distinguish the plaintext of a given ciphertext without the corresponding decryption key. Specifically, it is impossible for an attacker from a different organization $org*$ to access the plaintext data corresponding to the ciphertext data belonging to org's clients. This is because org_1 keeps its decryption key confidential, and the IND-CPA makes it computationally infeasible for the attacker to gain any information about the ciphertext without any knowledge of the decryption key. □

6 Evaluation

GECO implementation. We built GECO on the codebase of HLF v2.5 [18]. GECO uses the BFV scheme [10, 19] imple-

No.	Name	⊕	⊗	Description
1	casino ♠	✓	✓	A coin flip game with biased odds: 49% chance to win, 51% chance to lose, both 0.5× stake.
2	convolution	✓	✓	Compute one-dimensional convolution on two vectors with different owners.
3	inner-product	✓	✓	Compute the inner-product of two vectors with different owners.
4	rebate	✓	✓	Currency rebate for qualifying expenditures exceeding a threshold.
5	taxing	✓	✓	Tax calculation and payment.
6	appraisal	✓		Appraise collectibles with confidential value estimates.
7	crowdfunding	✓		Raise funds from multiple owners for a single project.
8	election	✓		Determine the winner in a two-candidate election.
9	med-chain	✓		Medicine inventory management.
10	token-transfer	✓		Peer-to-peer token transfer.

Table 6: Example smart contracts used in the second workload. ⊕ and ⊗ indicate whether the contract uses FHE addition or multiplication, respectively. ♠ indicates that the contract is non-deterministic.

mented by Lattigo [32]. With default cryptographic parameters, GECO supports FHE arithmetic computation over 58-bit unsigned integers, satisfying the requirements of diverse contracts listed in Table 6. GECO uses the Groth16 NIZKP system [23] on the BN254 elliptic curve implemented by Gnark [13]. Same as existing systems [5,41] that use Groth16, our implementation requires a circuit-specific trusted setup to generate the verification key for each NIZKP circuit. This setup is a one-time procedure with negligible overhead.

Baselines. We compared GECO with four baselines: HLF [4], ZeeStar [41], GECO (w/o. CTM), and GECO (w/o. defense). HLF is one of the most popular permissioned blockchain frameworks in both industry and academia [22, 36, 37]. ZeeStar is a notable confidentiality-preserving blockchain that encrypts sensitive data using exponential ElGamal encryption [31] (a PHE scheme) and generates Groth16 NIZKPs to ensure the execution correctness. GECO (w/o. CTM) implements only the CEOV workflow without integrating the CTM protocol. GECO (w/o. defense) implements both the CEOV workflow and the CTM protocol, but lacks the defense mechanism against the NIZKP omission attack as specified in §4.3.

Workloads. We used two workloads for evaluation. The first one (§6.1 and §6.2) is *SmallBank* [25], a widely used benchmark for evaluating blockchain performance [36, 39]. SmallBank simulates the banking scenario and provides diverse contracts like token transfer. We evaluated the encrypted version of SmallBank, where each contract is re-written with APIs provided by libGECO (see Table 2) and Gnark. Our second workload (§6.3) consists of ten contracts that involve FHE addition and multiplication, as shown in Table 6. In §6.3, we evaluated GECO, GECO (w/o. CTM), and ZeeStar with these contracts to measure the performance improvement brought by the CTM protocol in diverse applications such as gaming (`casino`) and finance (`token-transfer`).

Metrics. We measured two metrics: (1) *effective throughput*, the average number of client transactions per second (TPS) that are committed to the blockchain, excluding aborted transactions; and (2) *commit latency* (known as *end-to-end latency*), measuring the time from client submission to transaction commitment. In addition, we reported the 99th percentile commit latency (tail latency) and reported the cumulative distribution function (CDF) of the commit latency.

System	Average Latency (s)					99% tail latency (s)
	P	E	O	V	E2E	
ZeeStar	n/a	n/a	n/a	n/a	3.11	6.85
HLF	n/a	0.44	0.91	0.19	1.54	5.03
GECO (w/o. CTM)	0.47	0.87	0.88	0.24	2.46	7.46
GECO	0.75	0.85	0.89	0.23	2.72	3.28

Table 7: Each phase's latency and the 99% tail latency of Figure 5b. The letters "P", "E", "O", and "V" denote the preprocessing, execution, ordering, and validation phases, respectively. The term "E2E" denotes the end-to-end latency.

Testbed. We ran experiments in a cluster with 20 machines, each with a 2.60GHz E5-2690 CPU, 64GB memory, and a 40Gbps NIC. The average node-to-node RTT was 0.2 ms.

Settings. We evaluated all systems with the permissioned setting, where all participants are explicitly identified. We ran each experiment ten times and reported the average of the metrics. For each system, we created five organizations, each with two executors and one hundred clients. For GECO-based systems (i.e., GECO, GECO (w/o. CTM), and GECO (w/o. defense)), we designated one executor as the lead executor for each organization. For HLF and GECO-based systems, we created four orderers running the PBFT [11] protocol.

In §6.1 and §6.2, we evaluated the systems' performance under conflicting transactions using the SmallBank workload. We designated 1% of the client accounts as *hot accounts*, and configured the *conflict ratio*, which denotes the probability of each transaction accessing the hot accounts.

Our evaluation focused on three primary questions.

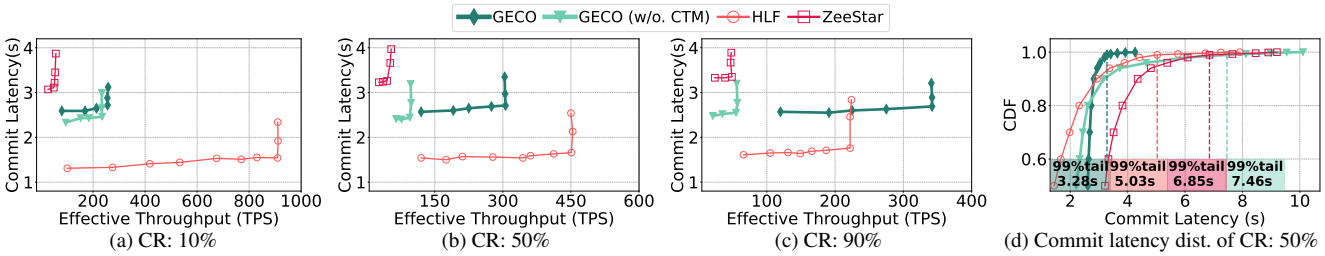
§6.1 How efficient is GECO compared to baselines?

§6.2 How robust is GECO to malicious participants?

§6.3 How efficient is GECO under diverse applications?

6.1 End-to-End Performance

We first evaluated the end-to-end performance in benign environments on four systems: GECO, GECO (w/o. CTM), ZeeStar, and HLF. In the benign environment, the network was stable, and all participants were correct. We conducted three experi-



(a) CR: 10% (b) CR: 50% (c) CR: 90% (d) Commit latency dist. of CR: 50%

Figure 5: End-to-end performance of GECO and baselines in benign environments with different conflict ratios.

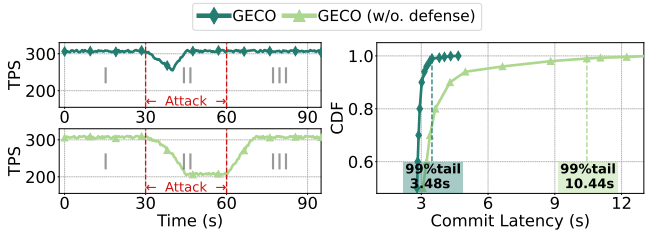
ments using the SmallBank workload with conflict ratios of 10%, 50%, and 90%, respectively. For each experiment, the benchmark tool generated a series of *Transfer* transactions (Listing 1). In each transaction, a sender client transferred a number of tokens to a receiver client. Note that both clients were randomly selected, and these clients may belong to different organizations. For aborted transactions, we repeatedly submitted them until they were successfully committed.

GECO achieved high effective throughput, outperforming both ZeeStar and GECO (w/o. CTM) by up to 7.14×. As shown in Figure 5, GECO achieved effective throughputs of 255, 307, and 343 TPS at conflict ratios of 10%, 50%, and 90%, respectively. In contrast, GECO (w/o. CTM) achieved only 235, 95, and 55 TPS, indicating a notable performance gap between GECO and GECO (w/o. CTM). This gap became more evident as the conflict ratio increased. ZeeStar performed even worse, achieving merely 54, 52, and 48 TPS, respectively. GECO achieved a low average end-to-end latency of 2.7s and the shortest 99% tail latency, as shown in Table 7.

We explain GECO's high performance in two aspects. Firstly, GECO's CTM protocol (§4.2) greatly reduced conflicting aborts. Although GECO incurred an 11% extra latency compared to GECO (w/o. CTM), it can be justified by the significant throughput gains. Secondly, GECO proved the execution correctness using the lightweight consistency check NIZKPs (§4.2), which were agnostic to the contract logic. In contrast, ZeeStar relied on the inefficient re-execution method (§1) for NIZKP generation. This enables GECO to achieve shorter commit latency than ZeeStar, as confirmed in Table 7.

Compared with HLF, which offers no data confidentiality guarantee, GECO incurred an average performance overhead of 32%. This overhead is attributed to three aspects. Firstly, GECO introduces an extra preprocessing phase, which merges correlated conflicting transactions and encrypts transaction parameters. Secondly, in the execution phase, GECO performs costly FHE computations and NIZKP generation. Lastly, in the validation phase, GECO verifies the consistency check NIZKPs. We believe that these overheads are necessary and practical to fulfill GECO's confidentiality guarantee.

GECO is suitable for contending scenarios. As Figure 5 shows, when the conflict ratio increased, GECO (w/o. CTM), ZeeStar, and HLF suffered from a notable decrease in throughput. However, GECO demonstrated an increase in throughput. Furthermore, GECO outperformed HLF with a 1.54x higher



(a) Effective throughput. (b) Latency distributions.

Figure 6: Performance under malicious participants.

throughput in the scenario with a 90% conflict ratio, despite the extra overhead for achieving GECO's confidentiality guarantee. This was attributed to the CTM protocol, which effectively tackled conflicting aborts and reduced invocations of expensive cryptographic primitives.

Overall, GECO ensures data confidentiality while achieving high performance, making GECO particularly suitable for safety-critical and performance-sensitive applications.

6.2 Robustness to Malicious Participants

We conducted NIZKP omission attack (§4.3) on GECO and GECO (w/o. defense) with the same settings as §6.1. We set the conflict ratio as 50%. We designated four benign organizations (O_B) and one malicious organization (O_M). The lead executor of O_M conducted NIZKP omission attack toward all transactions involving O_M clients. The experiment has three periods: (I) *pre-attack*, (II) *attack*, and (III) *post-attack*.

Our defense mechanism against the NIZKP omission attack (§4.3) is effective. Figure 6a shows that both GECO and GECO (w/o. defense) witnessed performance degradation at the onset of the attack. However, GECO quickly recovered its peak throughput, while GECO (w/o. defense)'s throughput remained poor until we terminated the attack. Figure 6b shows that GECO's tail latency barely changed during the attack (compared to Figure 5d). In contrast, GECO (w/o. defense) witnessed notable degradation in tail latency as the transactions involving O_M were repeatedly re-submitted and aborted, wasting the computation resources of executors. These differences were due to GECO's defense mechanism, which successfully detected the malicious lead executor of O_M and early rejected the transactions involving O_M. Overall, GECO achieves high performance even in the presence of malicious participants, and thus is suitable for applications with high se-

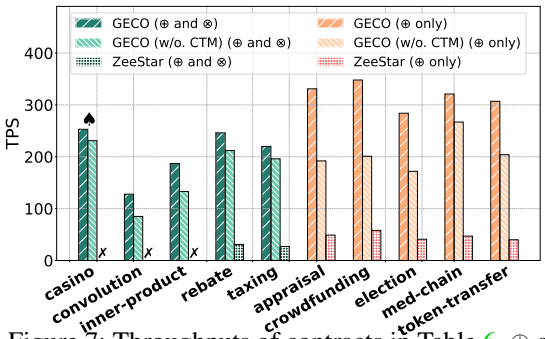


Figure 7: Throughputs of contracts in Table 6. ⊕ and ⊗ denote FHE addition and multiplication. ♠ is non-deterministic contracts. ✗ is contracts not supported by ZeeStar.

curity requirements like supply chain [36] and bidding [41].

6.3 Performance under Diverse Applications

We evaluated GECO, GECO (w/o. CTM), and ZeeStar using the second workload, which consists of ten diverse smart contracts (Table 3). As Figure 7 shows, GECO exhibited high performance in all evaluated contracts, achieving throughput ranging from 120 TPS (`convolution`) to 348 TPS (`crowdfunding`). The CTM protocol delivered notable throughput gains, especially in contracts where conflicts are prevalent, such as `election` and `token-transfer`. Furthermore, GECO can support general applications with contracts that are non-deterministic (e.g., `casino`) and involve foreign values (e.g., `inner-product`). In contrast, existing confidentiality-preserving blockchains (e.g., ZeeStar) can only support deterministic contracts and do not support arbitrary arithmetic computations on foreign values.

In summary, GECO ensures data confidentiality while achieving high performance for general smart contracts, enabling the deployment of diverse applications developed in general programming languages like Go [4]. Thanks to GECO's contract logic-agnostic trusted execution (§4.2), we can easily integrate more advanced cryptographic primitives like CKKS [44], which support floating point FHE computations, without modifying our protocol.

7 Conclusion

We present GECO, a high-performance confidential permissioned blockchain framework for general non-deterministic smart contracts and cryptographic primitives. GECO ensures the correctness of transaction executions by efficiently generating NIZKPs that are agnostic to contract logic. Moreover, our CTM protocol effectively enhances GECO's performance in contending applications, illustrating a new approach for tackling conflicting aborts. Extensive evaluation demonstrates that GECO achieves superior performance compared to baselines, making GECO an ideal choice for a wide range of blockchain applications that desire both data confidentiality and high performance.

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