

BlockOPE: Efficient Order-Preserving Encryption for Permissioned Blockchain

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Presented at ICDE 2022



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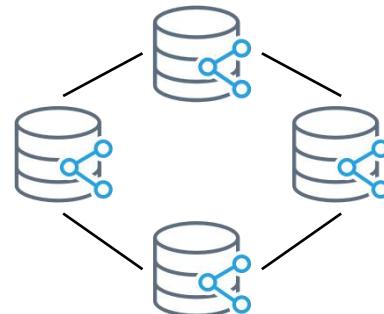
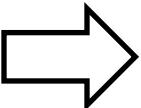
Background

- Blockchain, as a **tamper-evidence, traceable, multi-party jointly maintained** distributed ledger, can tackle trust problems among mutually distrusting parties.
- Permissioned blockchain inherits the above advantages, which is evolving into a platform for **data management and sharing** in many collaborative scenarios due to its higher throughput.

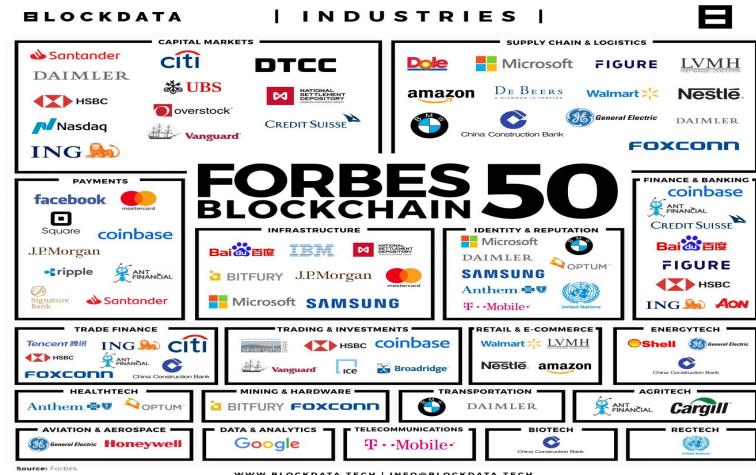
Application Scenarios:



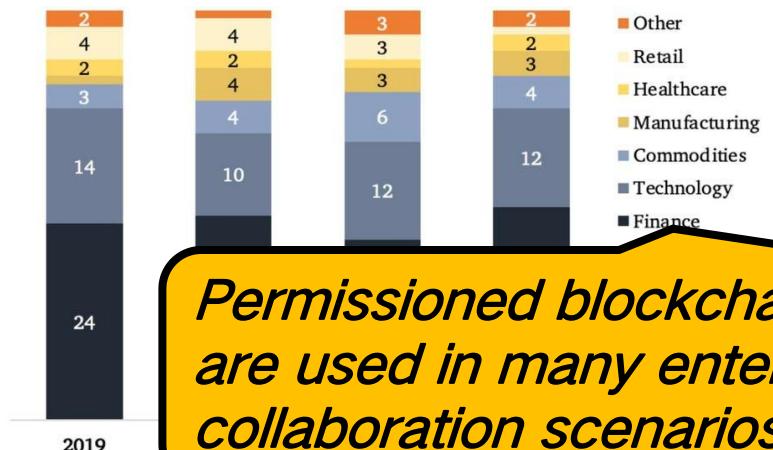
Cryptocurrency



Data Collaboration



Forbes Blockchain 50 (2020)



Permissioned blockchains are used in many enterprise collaboration scenarios

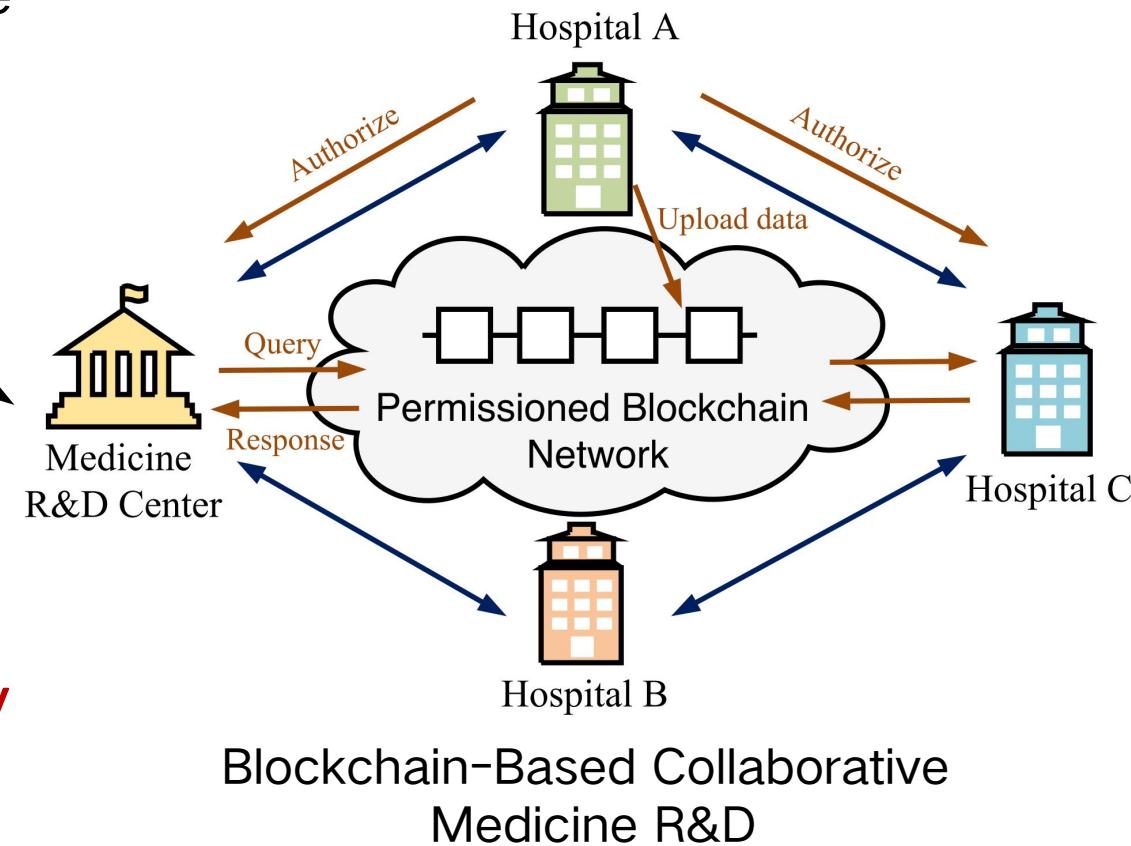
Forbes Blockchain 50 Categories (2019 ~ 2022) <https://www.forbes.com/sites/javierpaz/2022/02/08/2022-forbes-blockchain-50-a-closer-look/>

Background

- However, the data contents stored on blockchain are **plaintexts** , which can be exposed to the malicious nodes under the Byzantine environment, leading to **privacy breaches**.

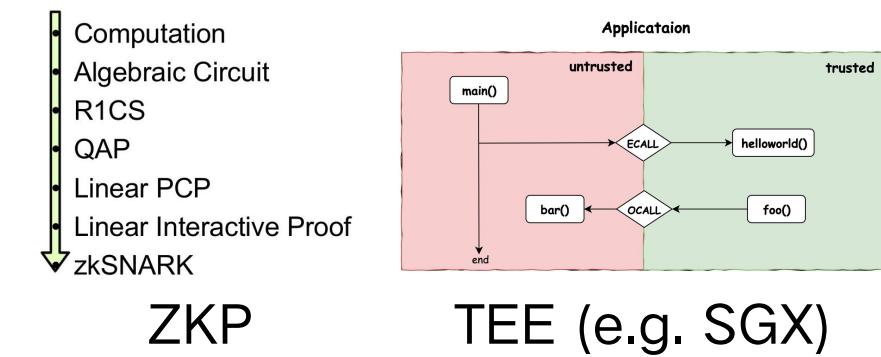
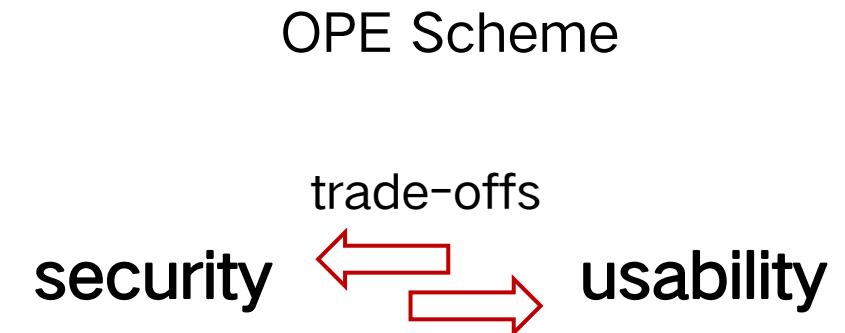
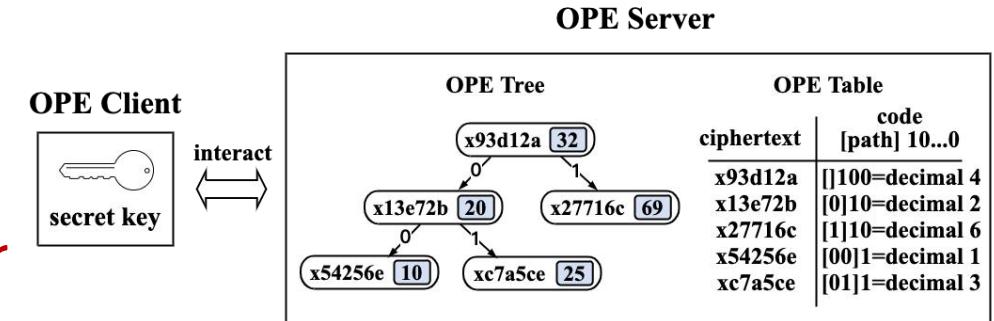
require privacy protection while allowing efficient queries to support blockchain-based data-sharing scenarios

- Order-Preserving Encryption(OPE) is an encryption scheme that balances **data privacy** and **data usability**.



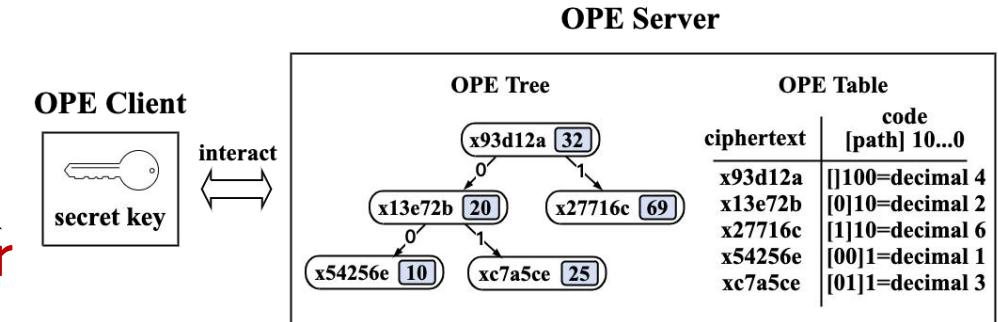
Related Works

- OPE schemes: widely used in outsourced databases and encrypted databases, allow the untrusted node to perform **order comparison over ciphertexts**.
- Other cryptographic schemes: Searchable Encryption scheme (**SE**), Order Revealing Encryption scheme (**ORE**), Fully Homomorphic Encryption (**HE**) ...
- Blockchain-related: researches try to protect data confidentiality to blockchain, including Homomorphic encryption (**HE**), Zero Knowledge Proof (**ZKP**) and Trusted Execution Environment (**TEE**).



Related Works

- OPE
constrained by limited use cases (the single client and single server model) and inherent performance limitations



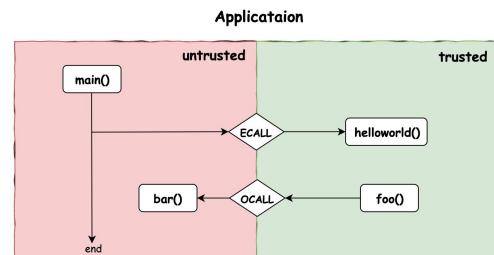
- can not achieve higher security and lower searching complexity simultaneously than OPE



- huge computation and memory costs / restricted by the hardware

Trusted Execution Environment (TEE).

data
graphic
and
computation
Algebraic Circuit
R1CS
QAP
Linear PCP
Linear Interactive Proof
zkSNARK



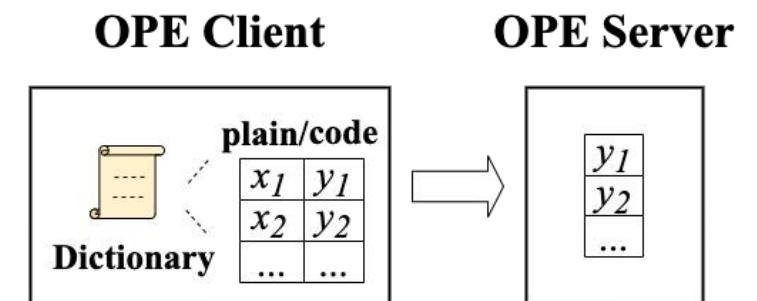
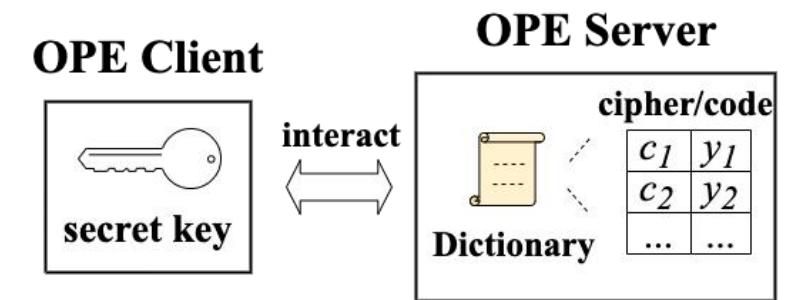
ZKP

TEE (e.g. SGX)

Challenges

- Conventional OPE schemes only consider the cloud environments (single client and single server model), which are **unfeasible for fully-replicated blockchain systems.**
- The inherent serial encoding processing of OPE will **burden the blockchain throughput**, especially for permissioned blockchain where performance is one of the main concerns.
- Provide **efficient queries over ciphertexts** while tackling the above two points.

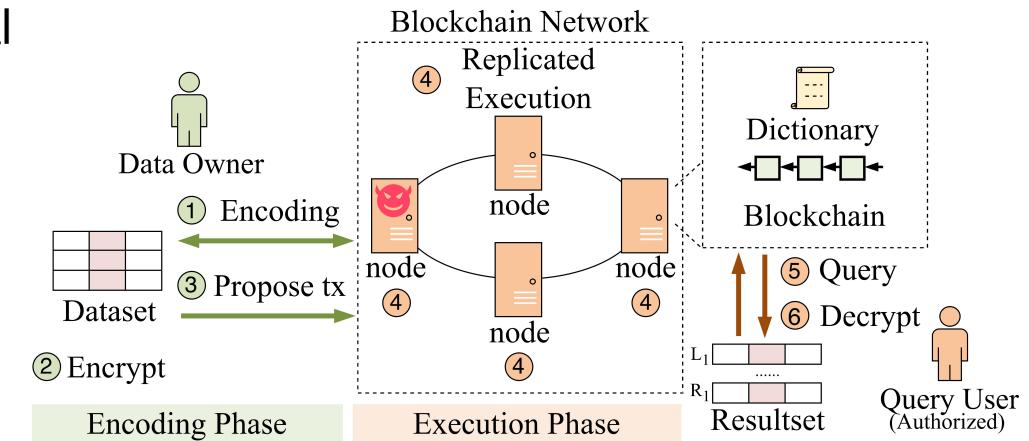
the dictionary is maintained
either on the client or
on the honest but curious server



Conventional OPE Schemes

Contributions

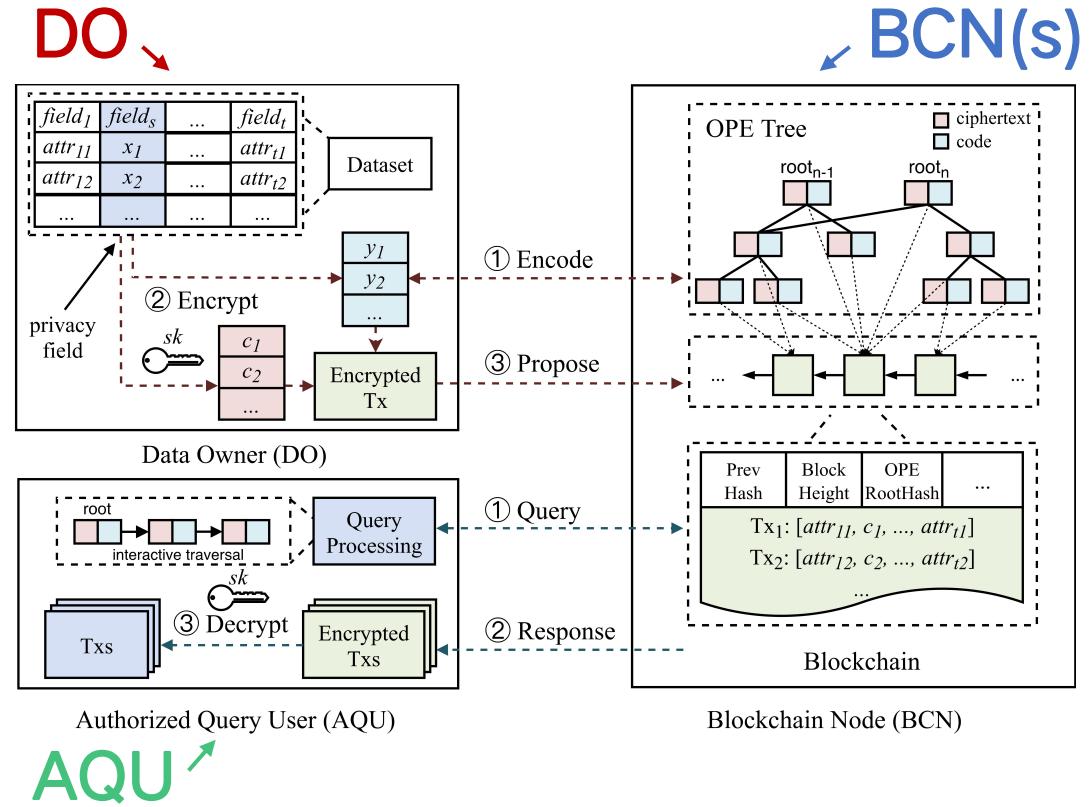
- **BlockOPE**: an efficient OPE scheme towards permissioned blockchain
 - Tech#1: Propose a **novel two-phase scheme** (encoding and execution phase)
 - Tech#2: Optimize the dictionary maintenance with **parallel processing and conflict-reducing** design
 - Tech#3: Leverage an **adaptive cache** to improve the query performance
- A prototype BlockOPE integrated with a permissioned mini-blockchain
- Experimental evaluations and theoretical analysis of the prototype
 - Verified proposed scheme is feasible and practical



Overview of BlockOPE

Threat model

- **DO** (Data Owner):
 - **DO** owns the data to be encrypted, thus is trusted.
 - **DO** uploads ciphertexts to the blockchain to store the data and claim the data authority.
- **AQU** (Authorized Query User):
 - **AQU** acquires the shared data by querying blockchain for ciphertexts provided by **DO**.
 - **AQU** and **DO** are mutually trusting while both of them share no trust with BCNs.
- **BCN** (Blockchain Node):
 - All **BCNs** cooperate to host the blockchain.
 - At most f **BCN(s)** can be malicious or Byzantine out of n **BCNs** such that $n \geq 3f + 1$.

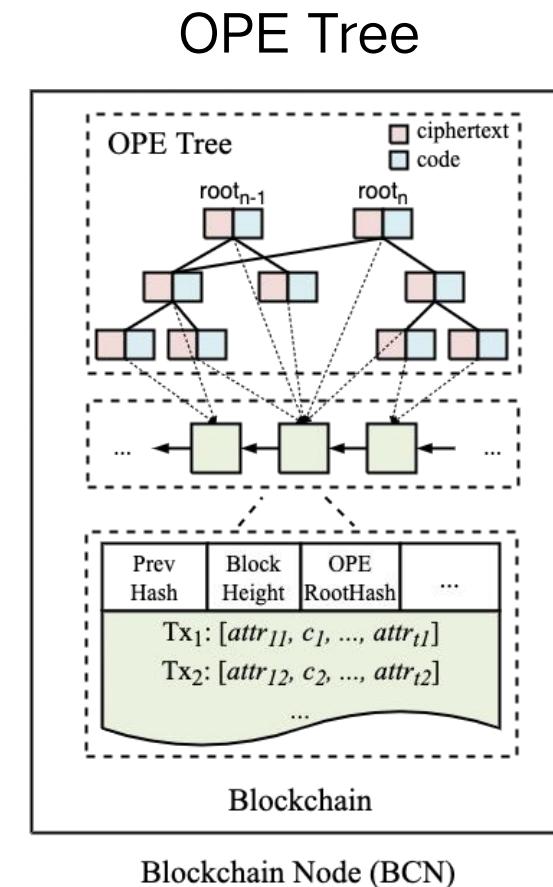


AQU↑

DO, AQU and BCNs of BlockOPE

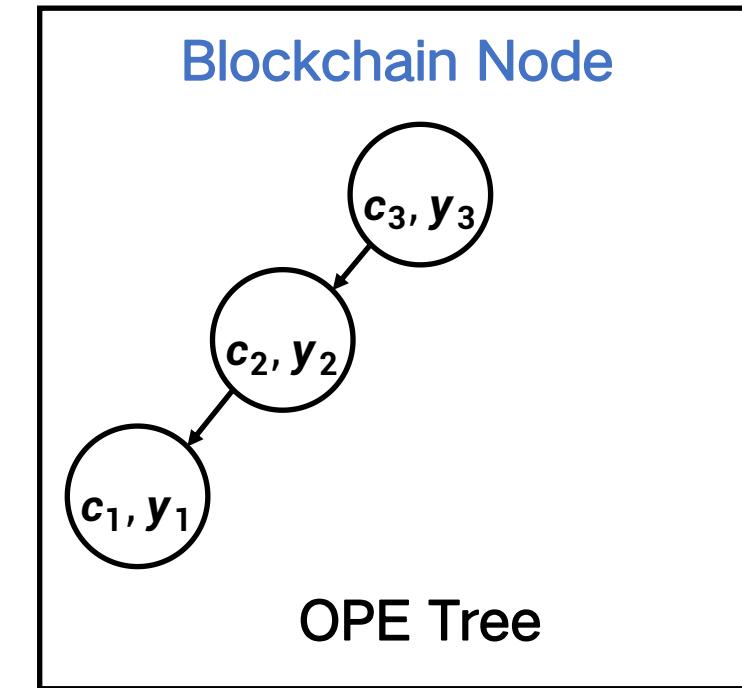
Methodology

- OPE Tree:
 - The OPE Tree is a data structure of a collection of vertices in the form of $\langle c, y \rangle$. It can be seen as an index structure built on blockchain transactions, meaning each vertex links to its corresponding transaction.



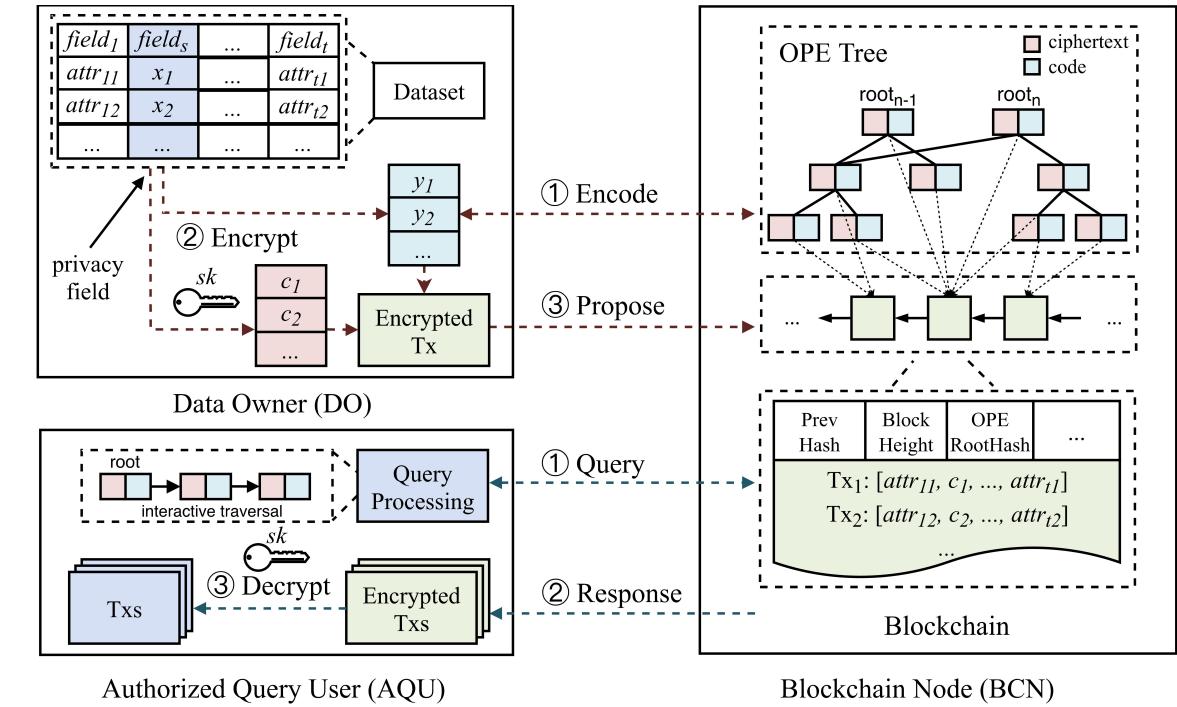
Methodology

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 - *Definition:* The OPE Tree T is a binary search tree consisting of a set of vertices, $\forall \text{ vertex } v = \langle c, y \rangle \in T$, $c = \text{Encrypt}(x)$, $y = \text{Encode}(x)$, where x is the plaintext of private data.



Methodology

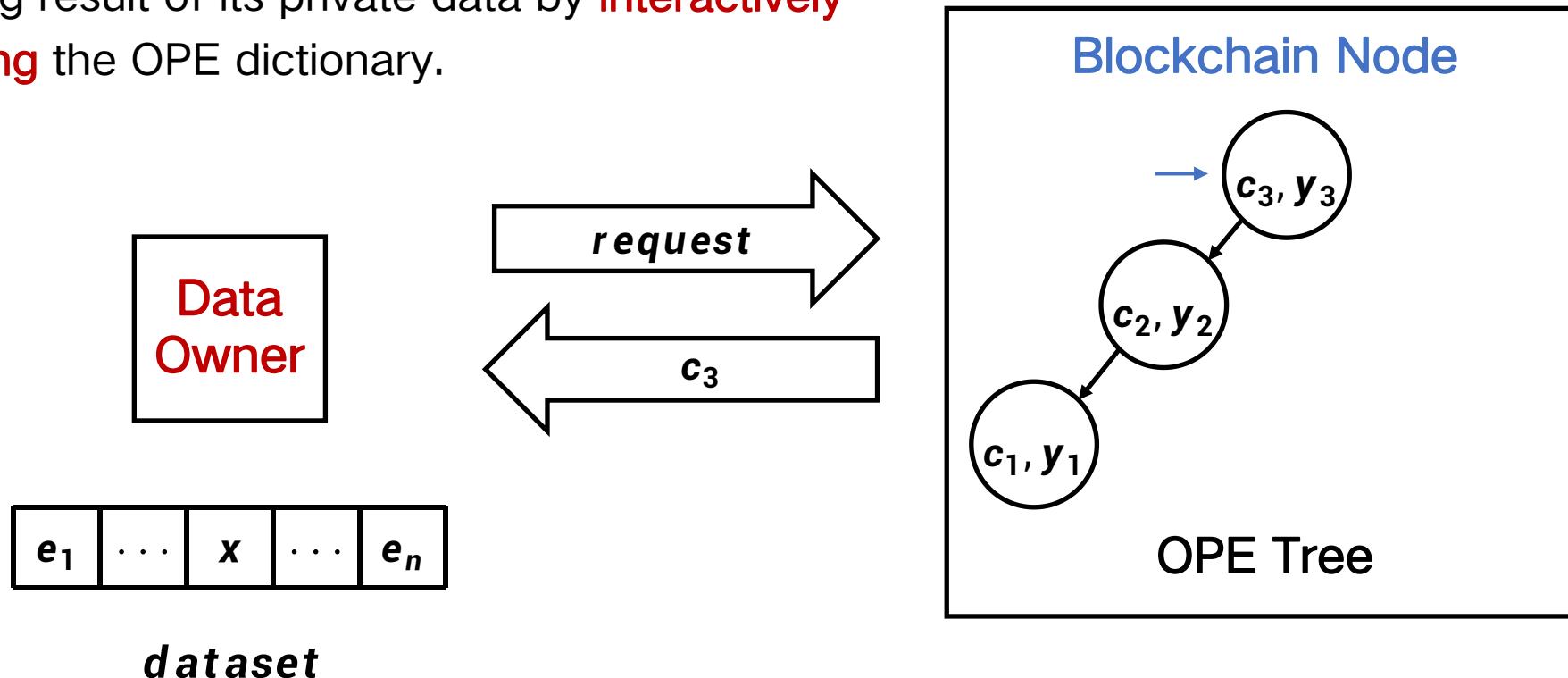
- Serial Two-phase BlockOPE:
 - Encoding Phase
 - DO interacts with BCN(s) to get the encoding result of its private data.
 - Execution Phase
 - DO sends the order-preserved codes to BCN(s) as a transaction.
 - BCNs execute agreed transactions to update the OPE Tree.



Processing of BlockOPE

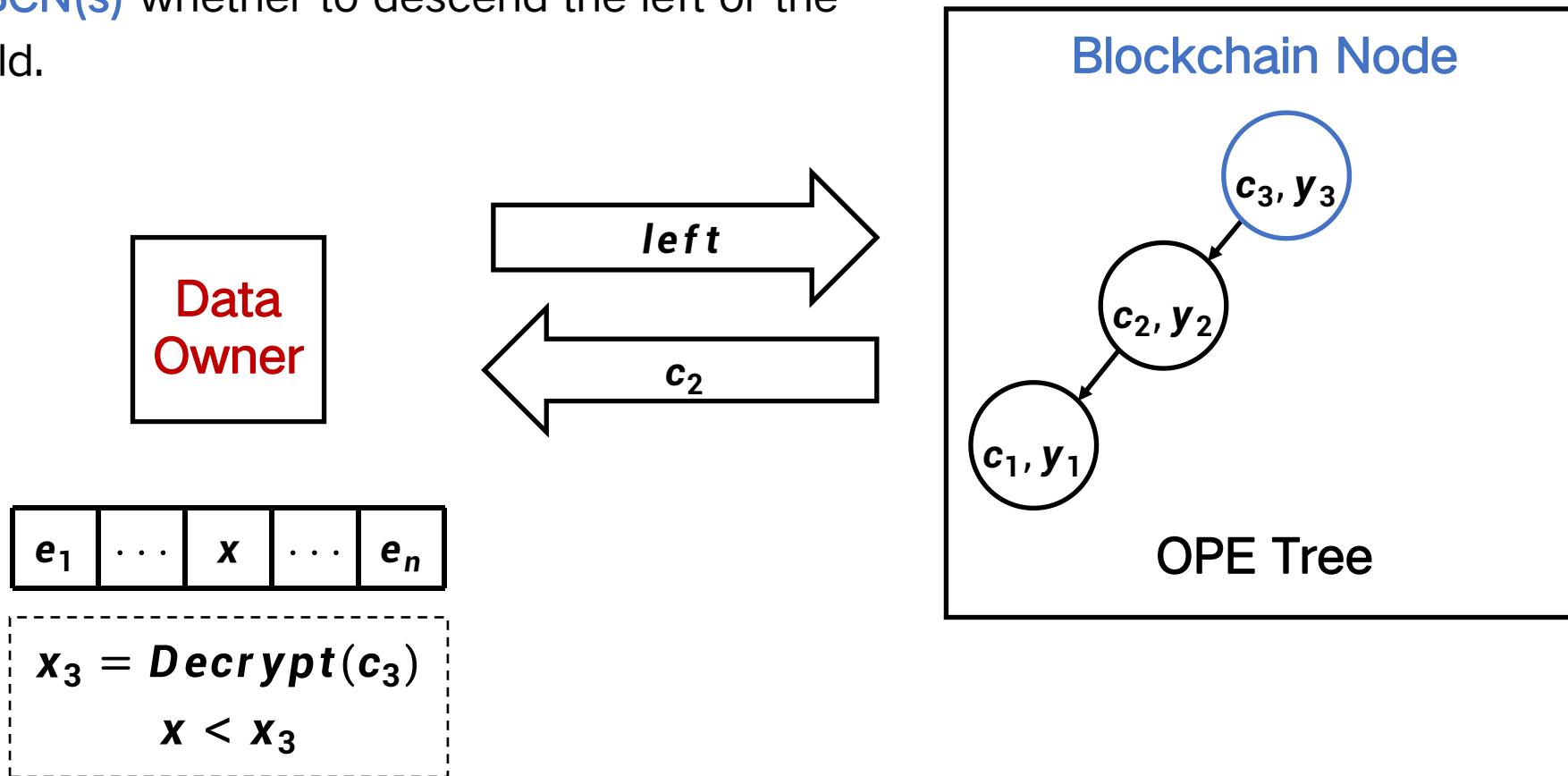
Methodology

- Encoding Phase:
 - DO sends an encoding request to BCN(s) to get the encoding result of its private data by **interactively traversing** the OPE dictionary.



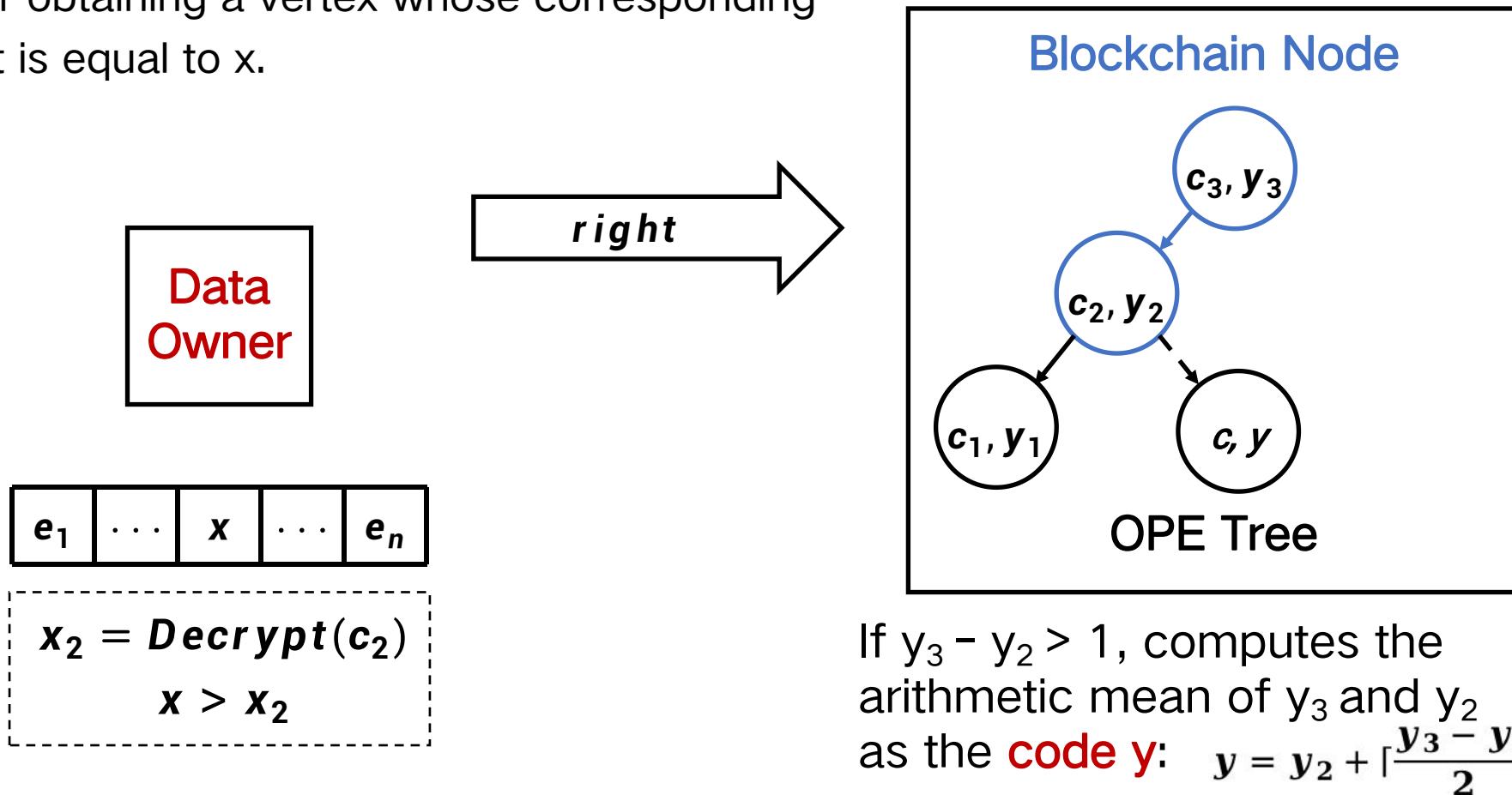
Methodology

- Encoding Phase:
 - DO decrypts c_3 to x_3 and compares x_3 with x to inform BCN(s) whether to descend the left or the right child.



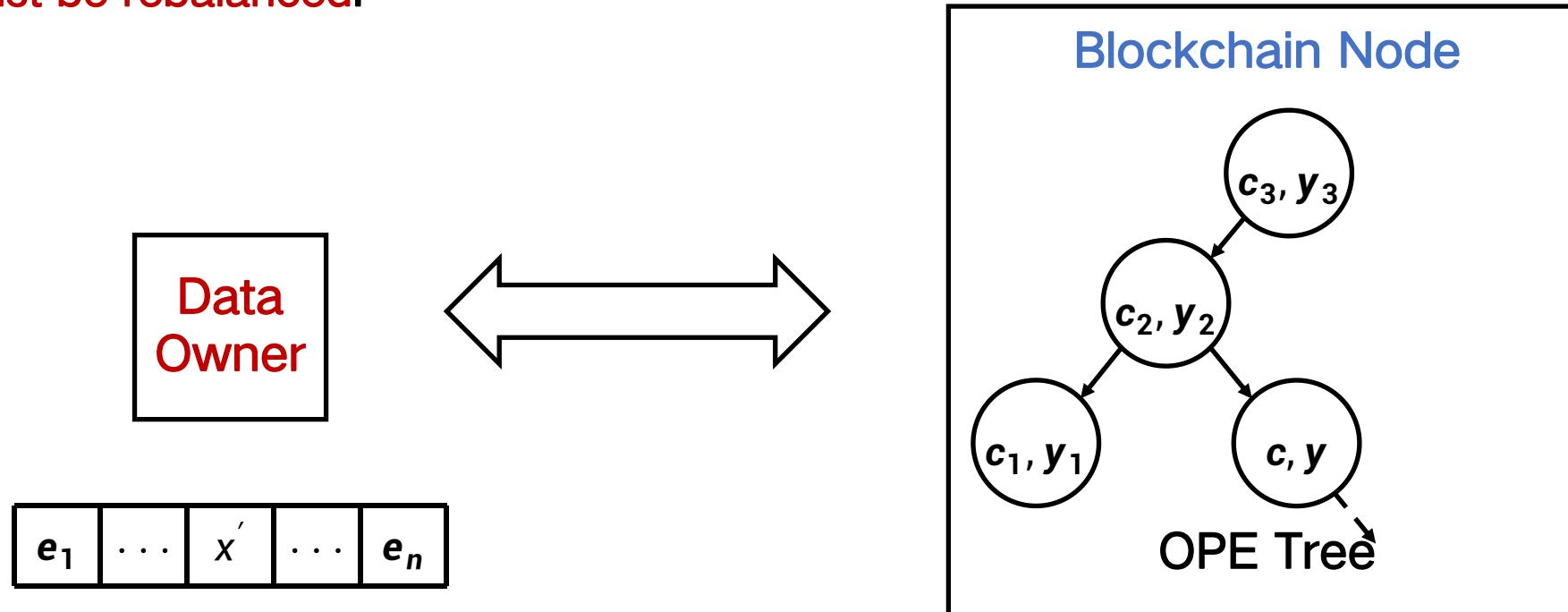
Methodology

- Encoding Phase:
 - Interactive operations end with arriving at **an empty vertex** or obtaining a vertex whose corresponding plaintext is equal to x .



Methodology

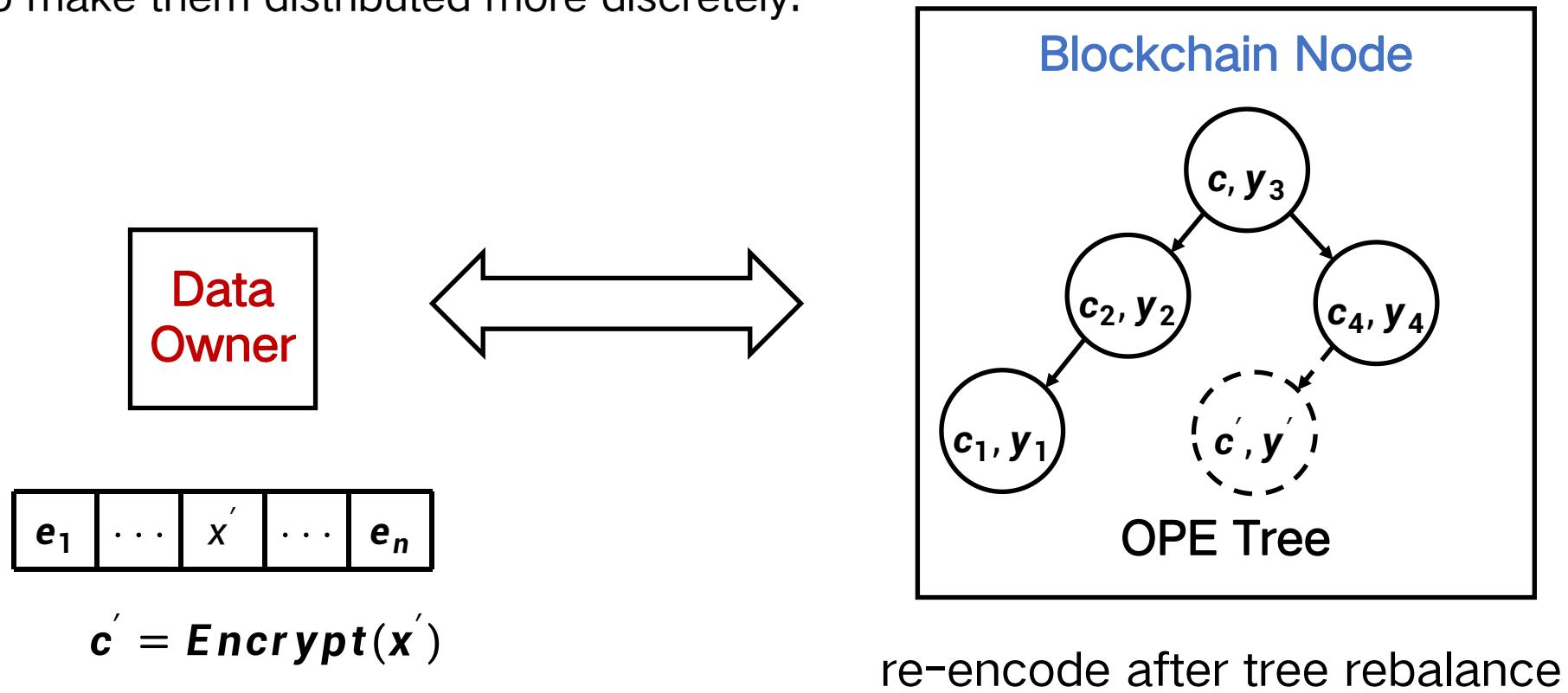
- Encoding Phase:
 - If the code space has been run out and **the OPE Tree must be rebalanced.**



If $y_3 - y_2 = 1$,
the OPE Tree needs to be
rebalanced

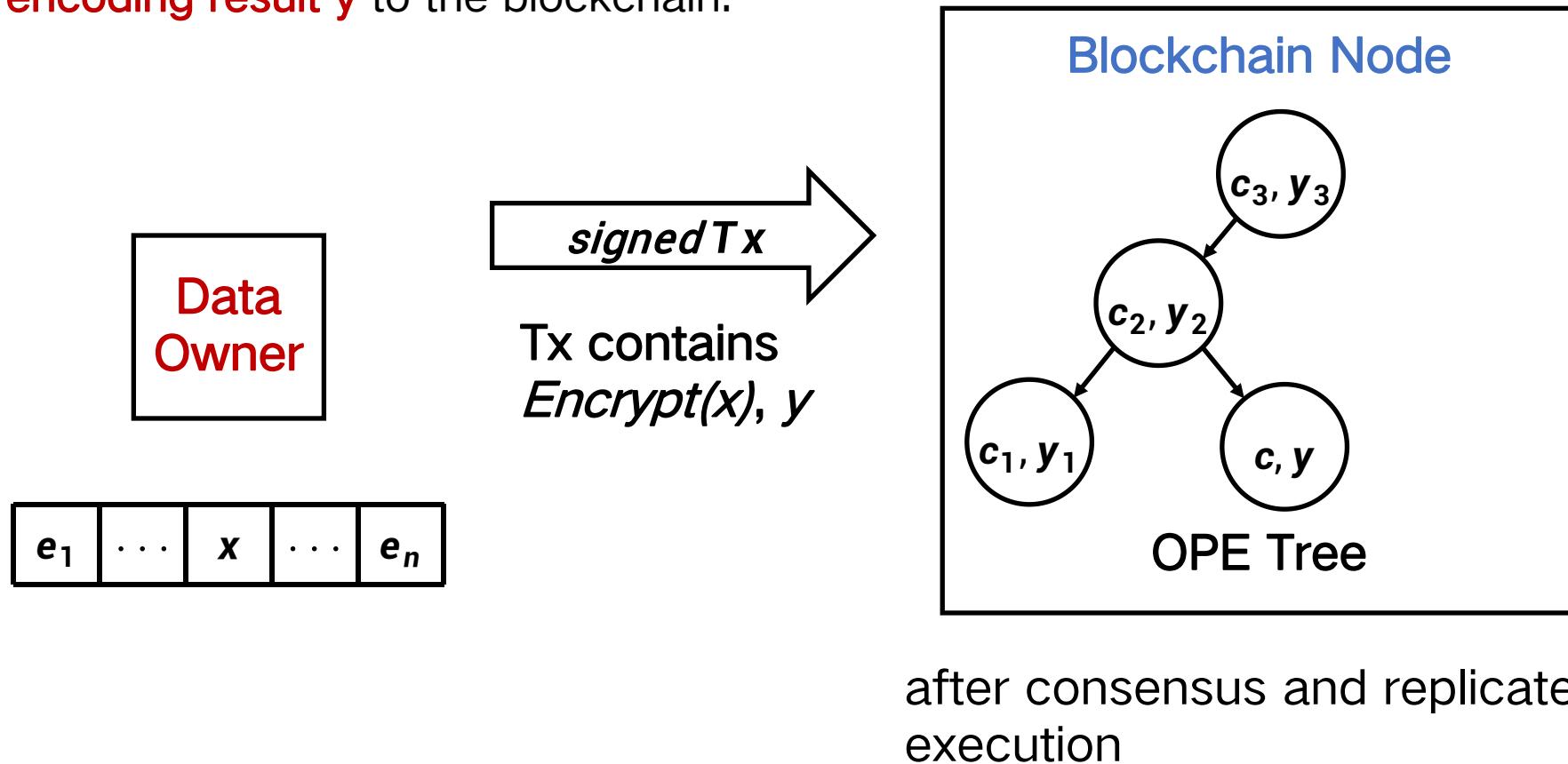
Methodology

- Encoding Phase:
 - Rebalance of OPE Tree: re-encoded all the existing codes to make them distributed more discretely.



Methodology

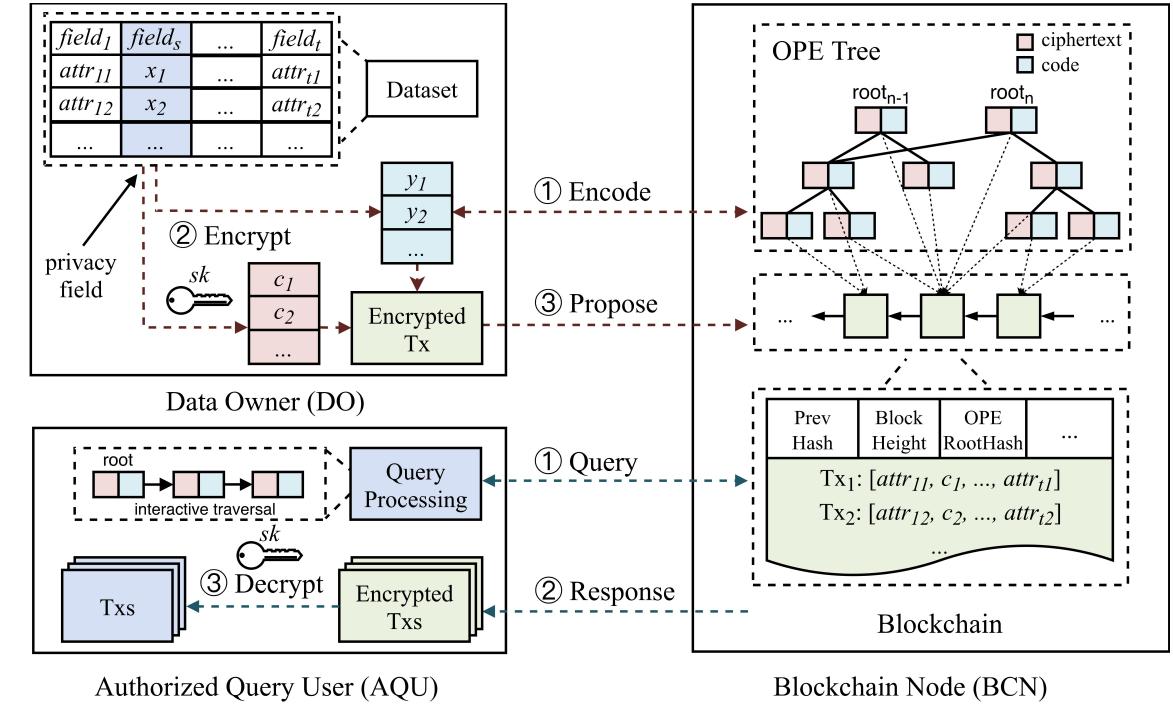
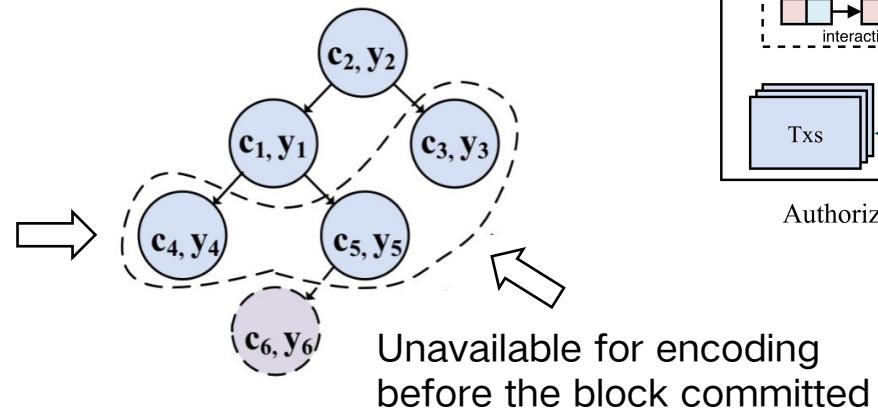
- Execution Phase:
 - DO sends a transaction containing **the ciphertext c** and **the encoding result y** to the blockchain.



Optimization

- Parallelizing Two-phase BlockOPE:
 - Encoding Phase
 - encode multiple plaintexts **in parallel based on snapshots.**
 - Execution Phase
 - summon the updates and employ parallel execution.

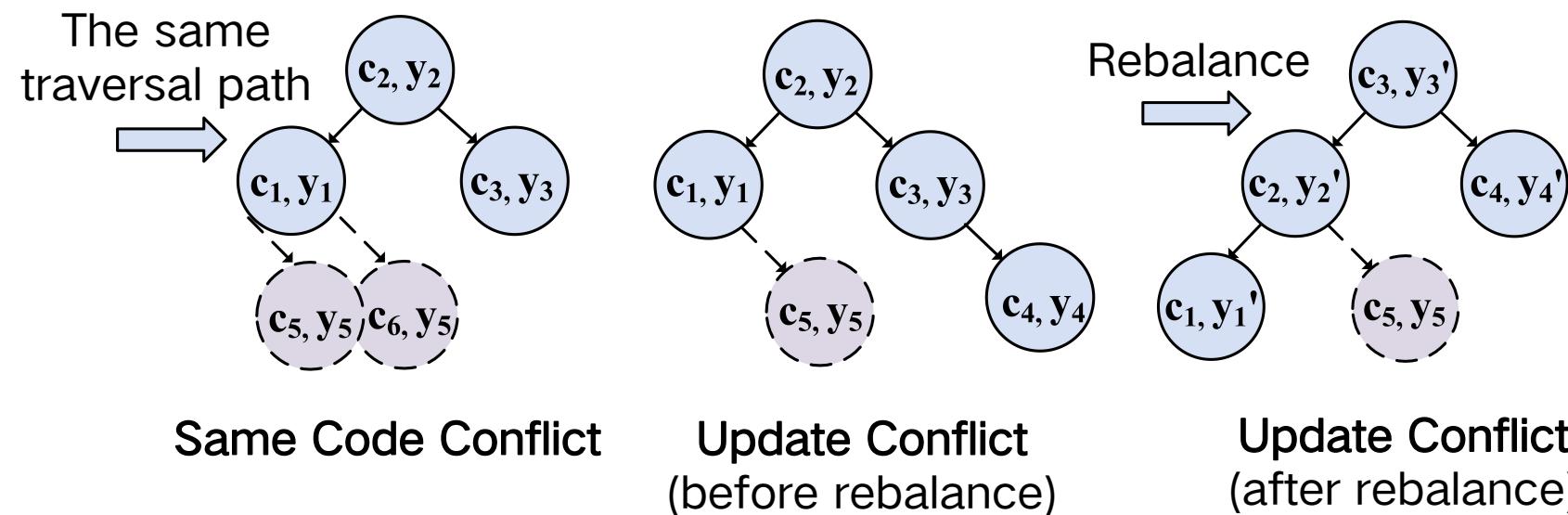
Transaction execution writes the vertices **at the bottom of the OPE Tree**



Processing of BlockOPE

Optimization

- Reducing Conflicts:
 - The two-phase OPE scheme will **cause conflicts**, resulting in codes generated in the encoding phase cannot be appended in the execution phase.
 - **Same Code Conflict(SCC)**: multiple encoding requests for different plaintexts obtain the same traversal path in the OPE Tree.
 - **Update Conflict (UC)**: the OPE Tree is rebalanced before appending the codes.



Optimization

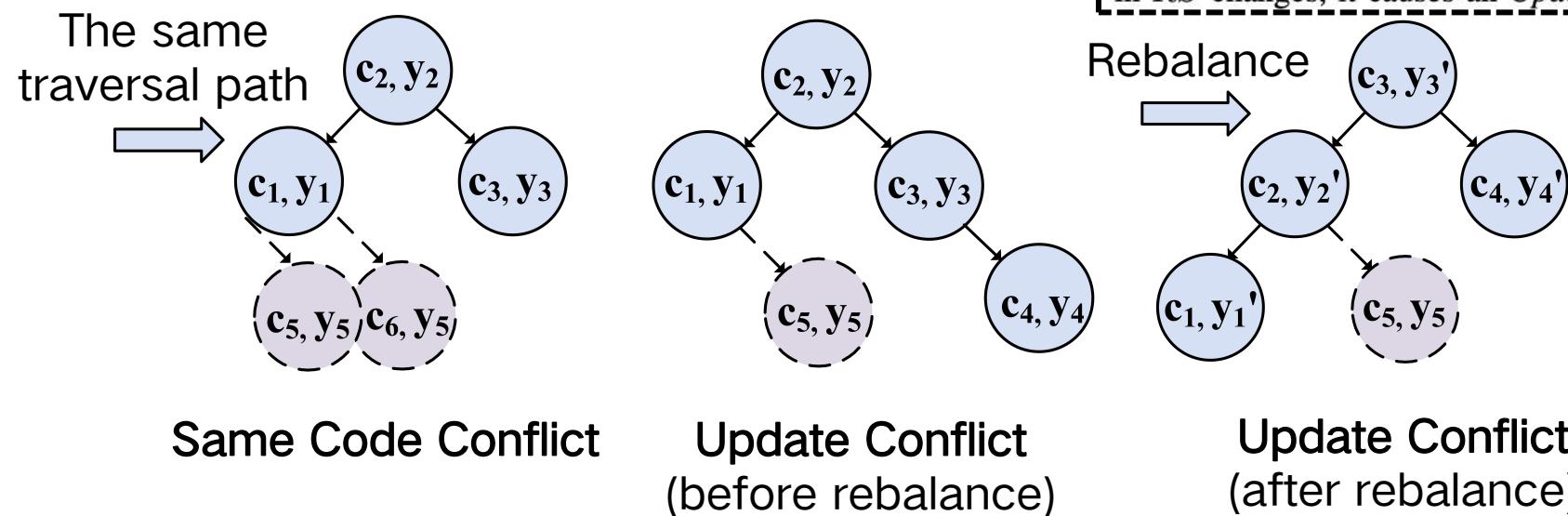
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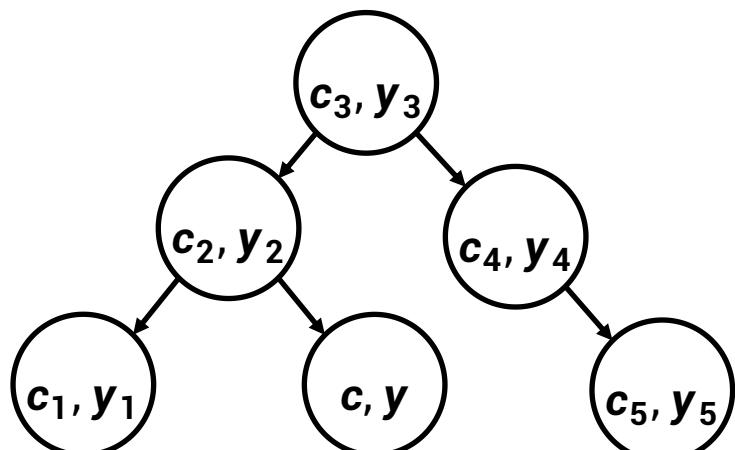
Definition 3: Same Code Conflict (SCC). Given $x_1, x_2 \in \Phi$ and $x_1 \neq x_2$, if \exists mappings $x_1 \rightarrow y$ and $x_2 \rightarrow y$, where $y \in \Upsilon$, it causes a *Same Code Conflict*.

Definition 4: Update Conflict (UC). Given $x \in \Phi$, encoding x to $y \in \Upsilon$, this encoding relies on a set of vertices RS . Before appending vertex $\langle c, y \rangle$ to the OPE Tree, if any vertex in RS changes, it causes an *Update Conflict*.

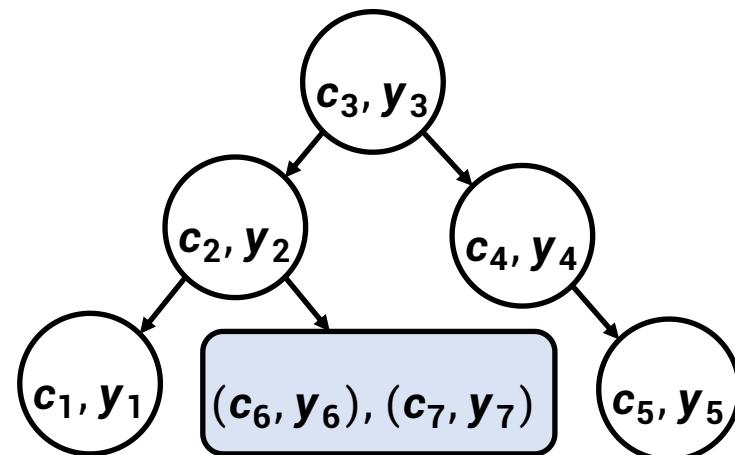


Optimization

- Reducing Conflicts:
 - **Randomized encoding**
 - add a noise ϵ to eliminate the possibility of distinct plaintexts encoded to the same code.
 - **Undecided-zone (UDZ) structure**
 - a UDZ stores multiple vertices whose codes are **non-order-preserving but within a certain range**.



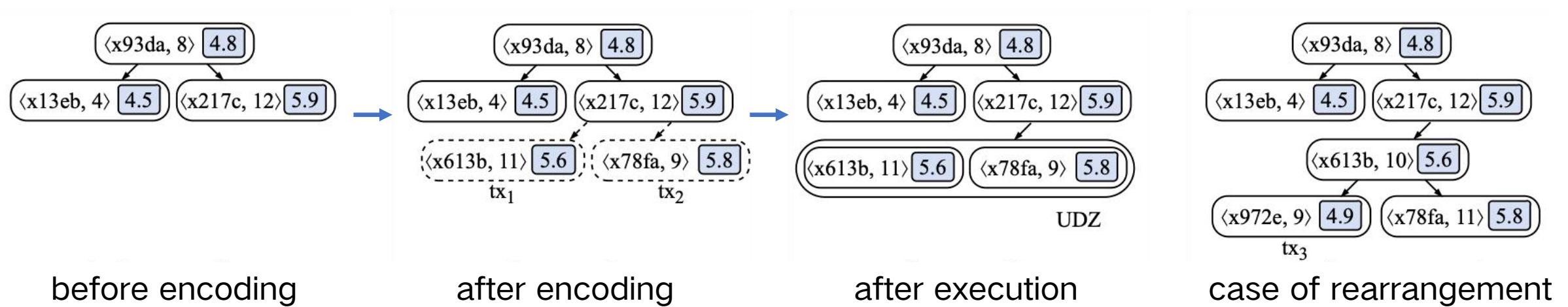
$$\mathbf{y} = \mathbf{y}_k + \lceil \frac{\mathbf{y}_{k+1} - \mathbf{y}_k}{2} \rceil + \epsilon$$



undecided-zone

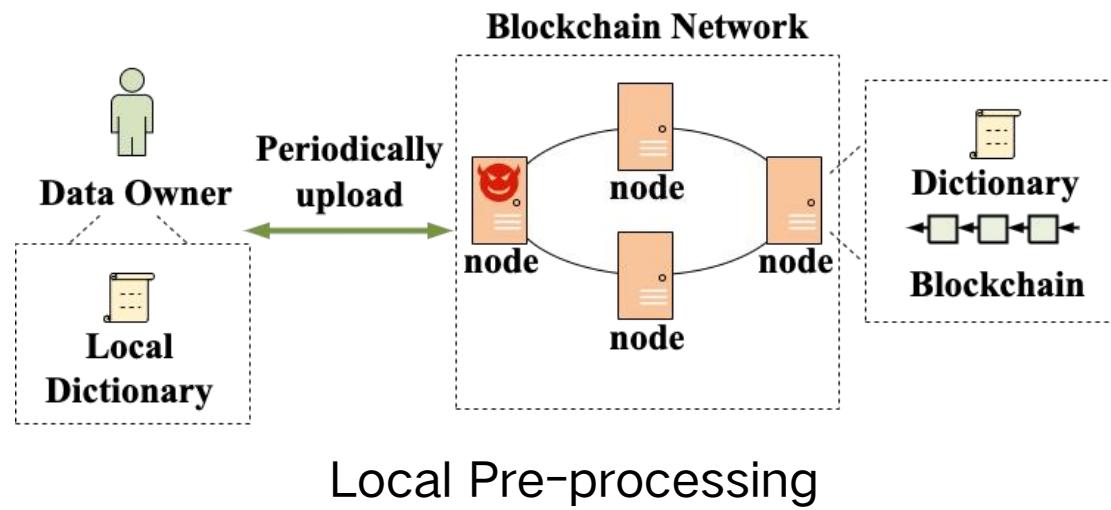
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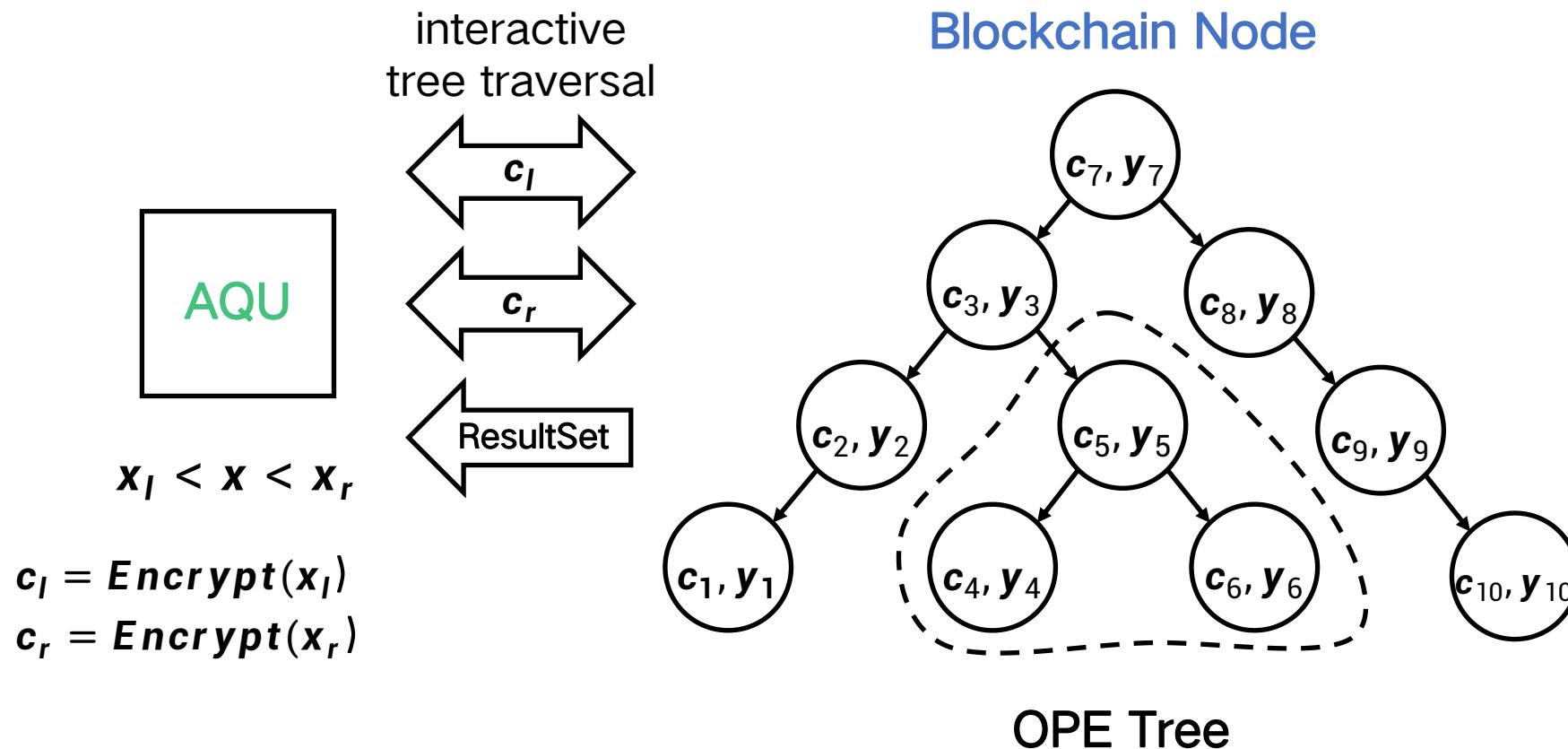
Optimization

- Local Pre-processing:
 - An optional optimization to accelerate the processing
 - making **trade-offs between conflicts and client storage.**
 - on-chain insertion and resolution play the role of **final guards** to guarantee the correctness of BlockOPE.



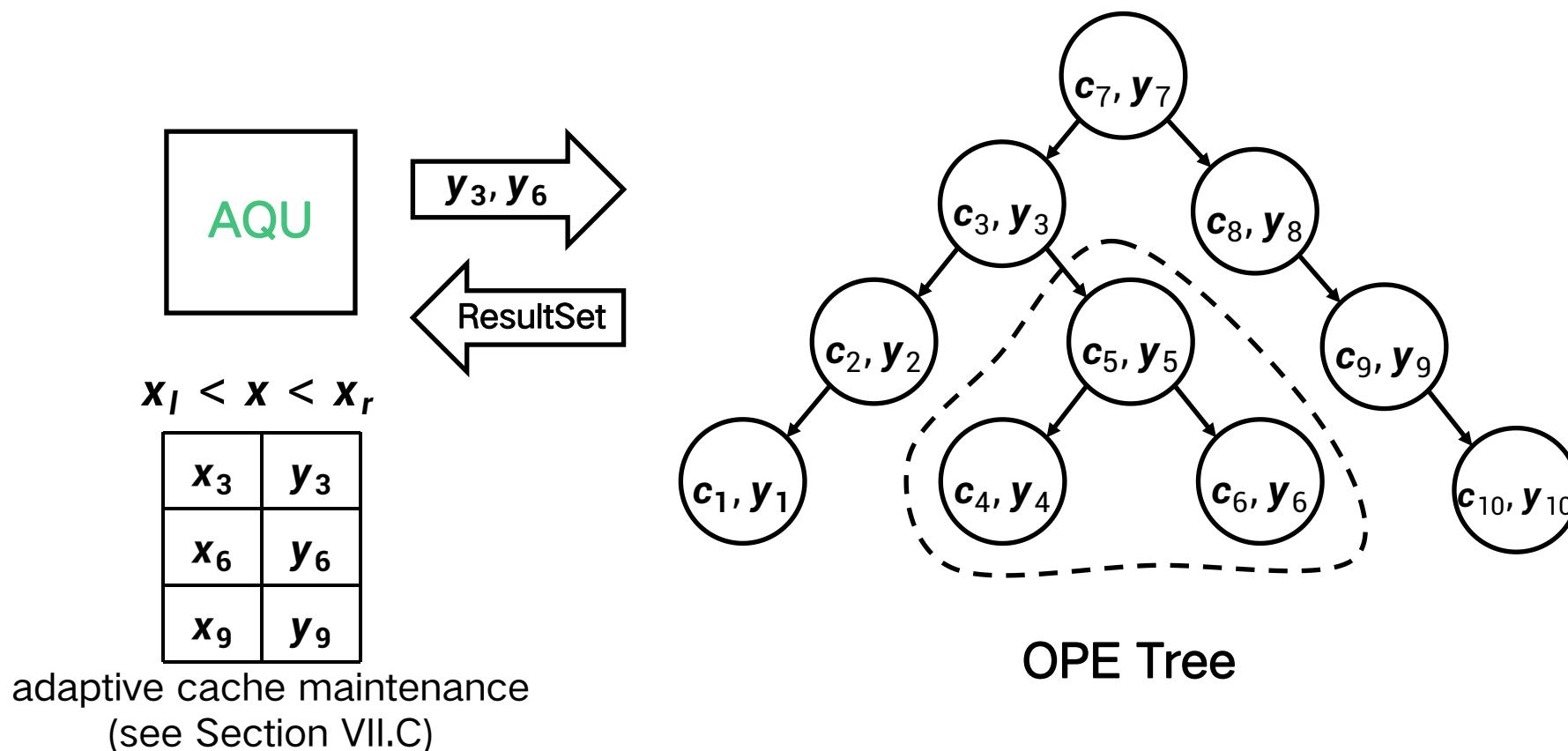
Query Processing

- Point/Range Query over ciphertexts:



Query Optimization

- Point/Range Query over ciphertexts:
 - **Adaptive Lightweight Cache**
 - cache with uniform intervals -> adjust the cache according to query inputs



Security

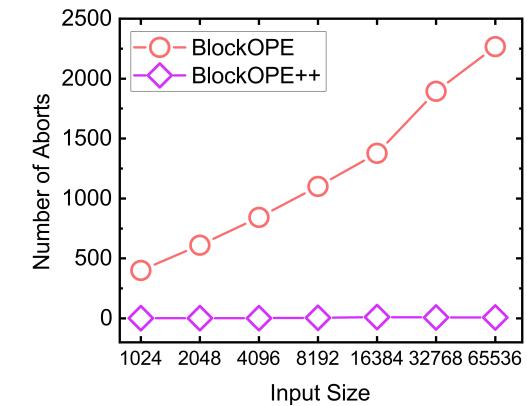
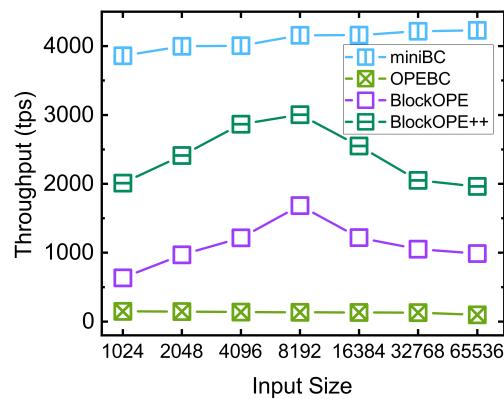
- IND-OCPA (indistinguishability under ordered chosen-plaintext attack)
 - Suppose there are two sequences of plaintexts: $S_0 = \{x_1^0, x_2^0, \dots, x_n^0\}$, $S_1 = \{x_1^1, x_2^1, \dots, x_n^1\}$, $x_i^0 < x_j^0 \Leftrightarrow x_i^1 < x_j^1$. Given the same initial state, if a malicious party cannot infer the corresponding plaintext sequence based on the encoding result, i.e., whether the encoding result is computed based on S_0 or S_1 . Then the order-preserving encryption scheme is IND-OCPA.
- Frequency-based attacks
 - the relative order information in UDZ remains unknown.
- Plaintext guessing attacks
 - need auxiliary information.
(see Section VIII.A)

Implementation

- A prototype BlockOPE integrated with a permissioned mini-blockchain
 - Integrating an open-source PBFT component of Hyperledger Fabric 0.6.
 - A cluster of 4 permissioned blockchain nodes.
- Systems Compared
 - No OPE Baseline (**miniBC**): We build a mini permissioned blockchain as the baseline system which does not adopt any OPE scheme.
 - Serial OPE (**OPEBC**): We apply serial OPE scheme to miniBC where one block contains at most one transaction to simulate traditional OPE scheme.
 - Parallel BlockOPE (**BlockOPE**): This system is the parallel BlockOPE prototype without reducing conflicts.
 - Efficient Parallel BlockOPE (**BlockOPE++**): This system is the parallel BlockOPE prototype combined all optimizations.

Experiment

- Performance Evaluation
 - Varying input size
 - Varying block size
 - Varying number of executing threads
 - Varying UDZ capacity
 - Evaluation of Conflict Reduction



Varying input size

plaintext domain size $M = 2^{16}$
code domain size $N = M^3 = 2^{48}$

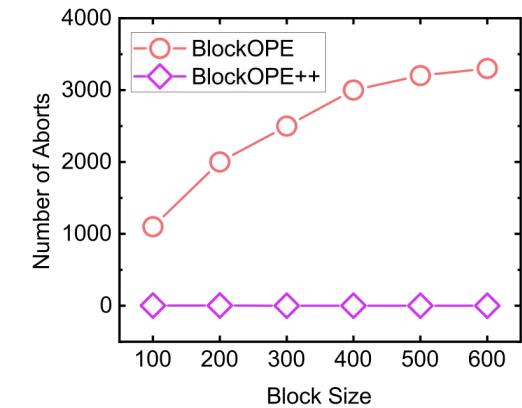
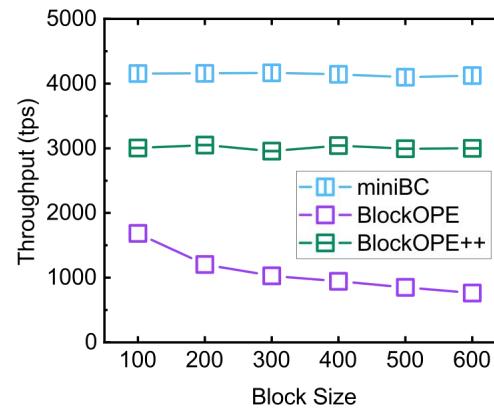
Parameter	Value	Parameter	Value
# of enc. threads	1 2 4 8 ...	input size	4096 8192 ...
# of exe. threads	1 2 4 8 ...	block size	100 200 ...
UDZ capacity	100 200 ...	distribution	uniform

Experiment

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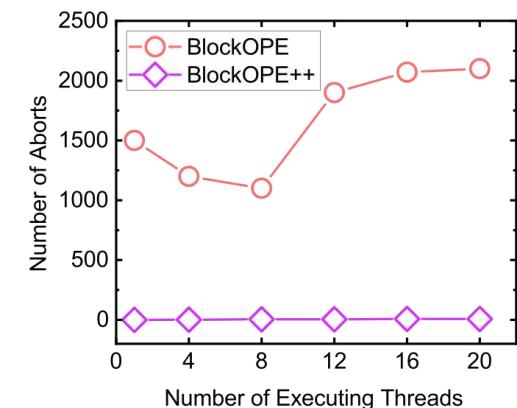
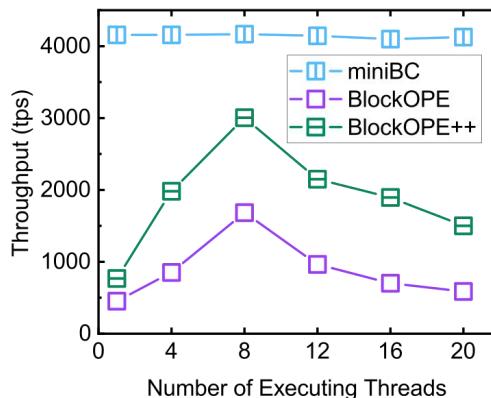
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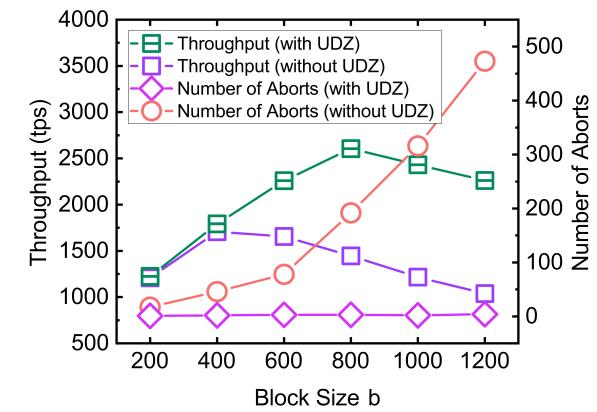
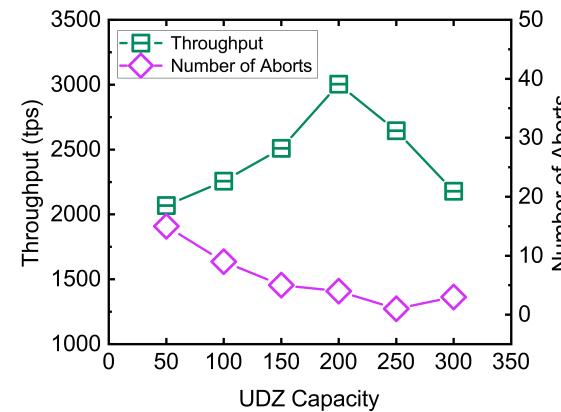
Varying number of executing threads

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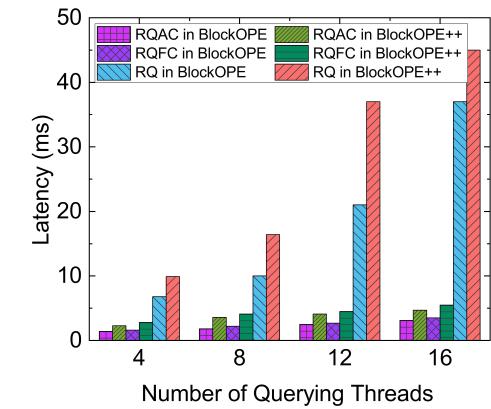
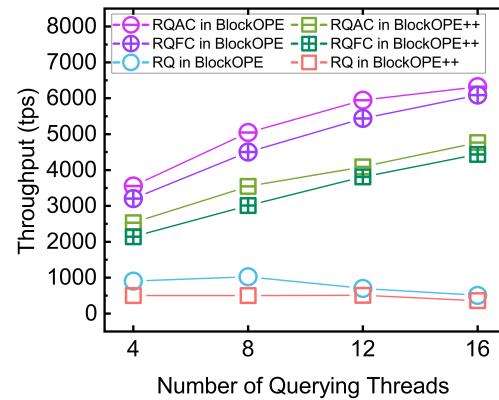
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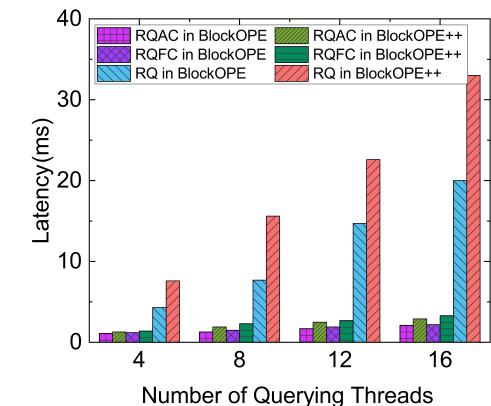
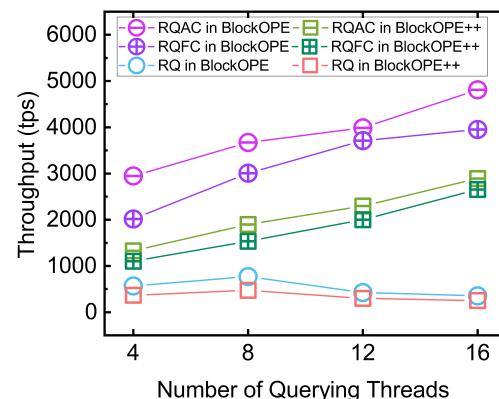
Varying UDZ capacity Evaluation of Conflict Reduction

Experiment

- Query Performance
 - Interactive range query (RQ)
 - Range query with fixed cache (RQFC)
 - Range query with adaptive cache (RQAC)



ResultSet size: 2000



ResultSet size: 4000

Conclusion

- BlockOPE is the **first blockchain-based OPE scheme** that brings privacy-protection to the blockchain while still preserving efficient order comparison primitives over ciphertexts.
- It provides efficient encoding through **parallelizing techniques and conflict reduction design**. It also utilizes an adaptive cache-based method for queries on ciphertexts.
- BlockOPE could be used to support **blockchain-based data sharing and collaboration scenarios** that require data privacy and efficient query ability.

THANKS !