BlockOPE: Efficient Order-Preserving Encryption for Permissioned Blockchain

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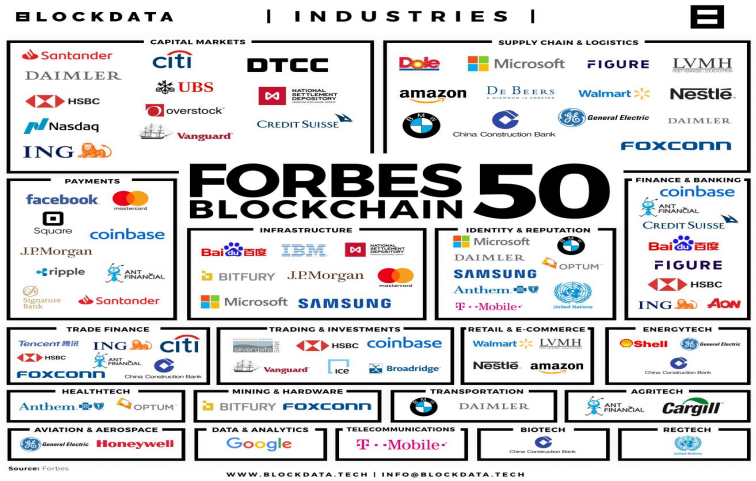
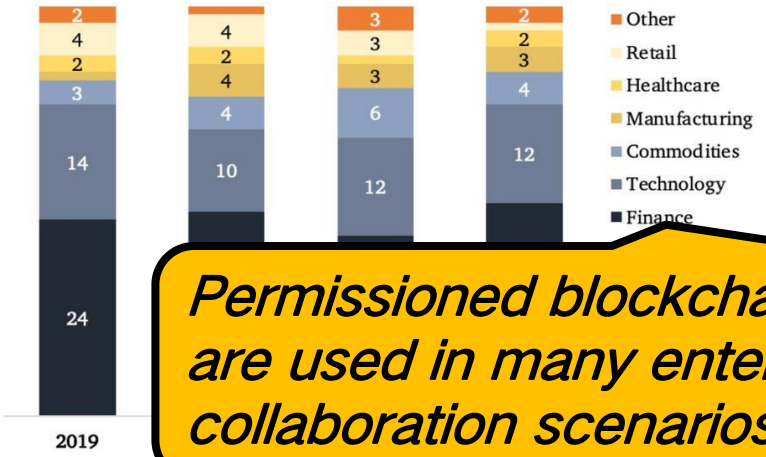
Background

- 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.



Forbes Blockchain 50 (2020)



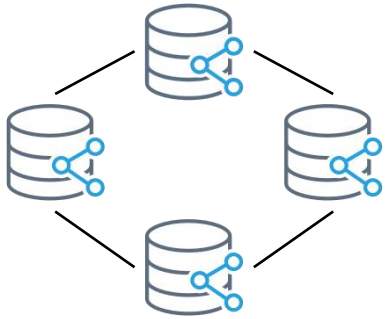
Permissioned blockchains are used in many enterprise collaboration scenarios

Forbes Blockchain 50 Categories (2019 ~ 2022)

https://www.forbes.com/sites/javierpaz/2022/02/08/2022-forbes-blockchain-50-a-closer-look/

Application Scenarios:

Cryptocurrency



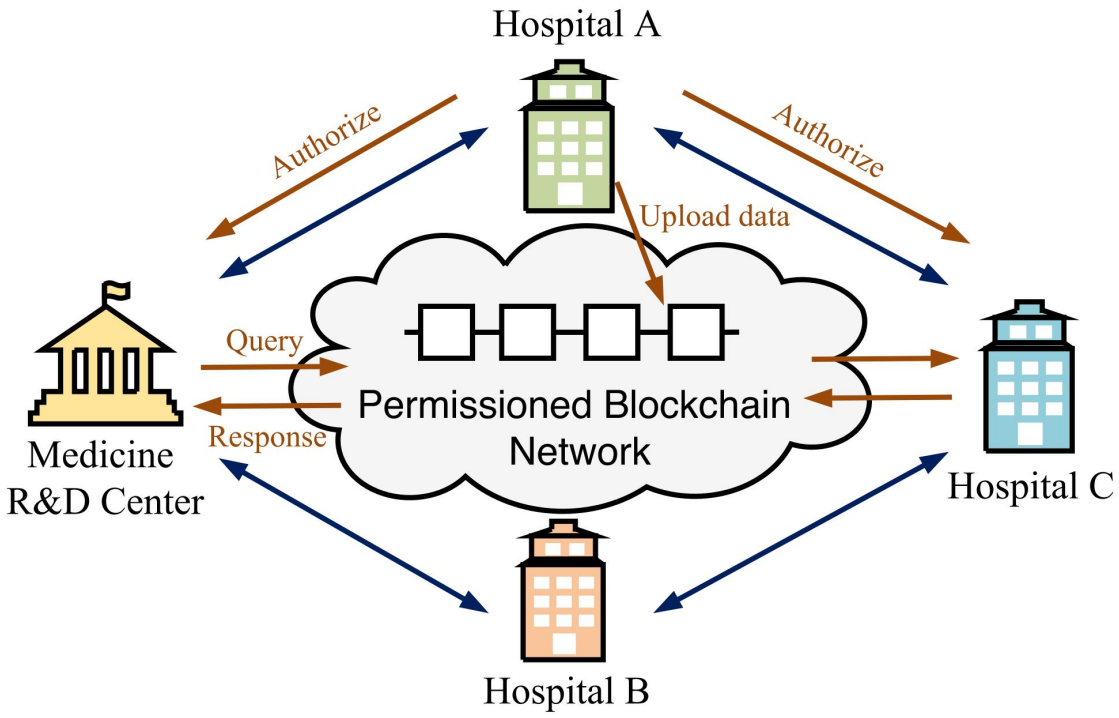
Data Collaboration

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

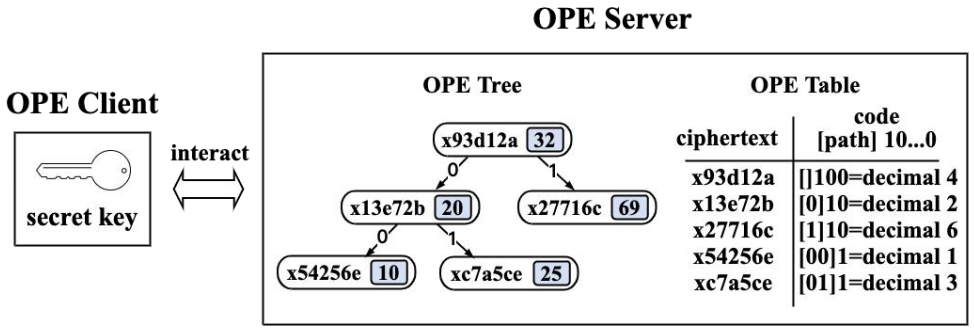
- Order-Preserving Encryption(OPE) is an encryption scheme that balances **data privacy** and **data usability**.



Blockchain-Based Collaborative Medicine R&D

Related Works

- OPE schemes: widely used in outsourced databases and encrypted databases, allow the untrusted node to perform **order comparison over ciphertexts**.



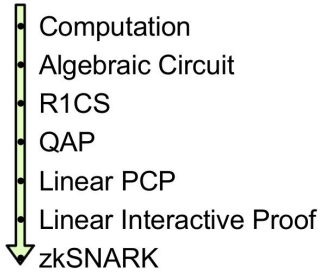
OPE Scheme

- Other cryptographic schemes: Searchable Encryption scheme (**SE**), Order Revealing Encryption scheme (**ORE**), Fully Homomorphic Encryption (**HE**) ...

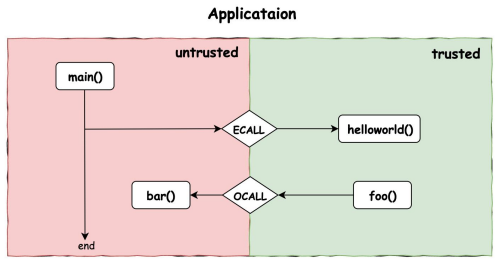
trade-offs

security ⇔ **usability**

- Blockchain-related: researches try to protect data confidentiality to blockchain, including Homomorphic encryption (**HE**), Zero Knowledge Proof (**ZKP**) and Trusted Execution Environment (**TEE**).



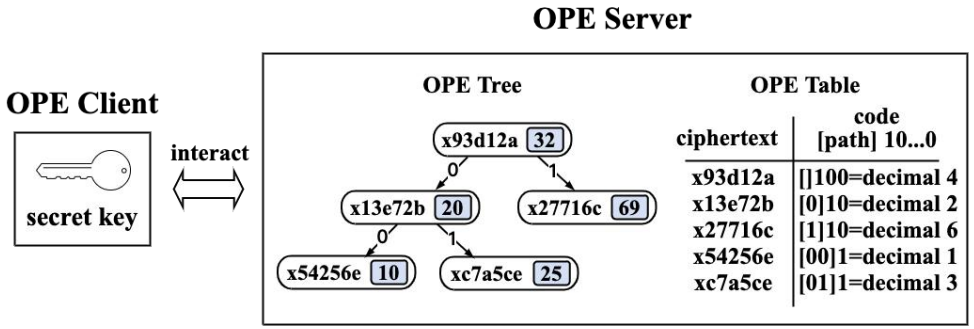
ZKP



TEE (e.g. SGX)

Related Works

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



OPE Scheme

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

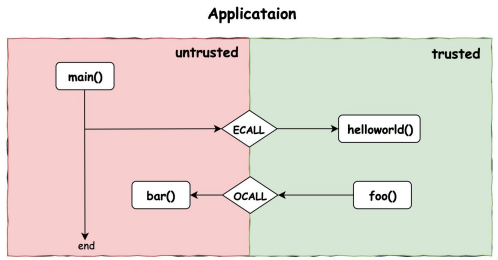
trade-offs

security ⇔ **usability**

- *huge computation and memory costs / restricted by the hardware*

- Computation
- Algebraic Circuit
- R1CS
- QAP
- Linear PCP
- Linear Interactive Proof
- zkSNARK

ZKP



TEE (e.g. SGX)

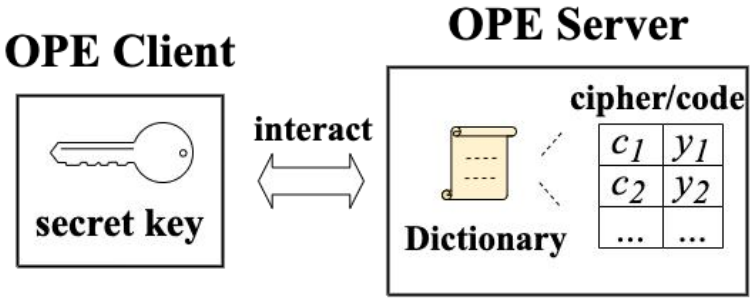
Challenges

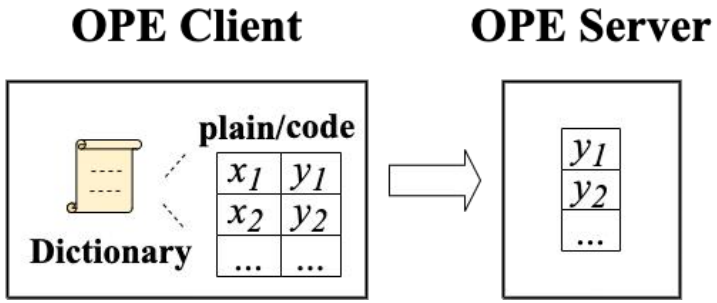
- Conventional OPE schemes only consider the cloud environments (single client and single server model, i.e., coordinated by the centralized node), which are **unfeasible for fully-replicated blockchain systems**.

- 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

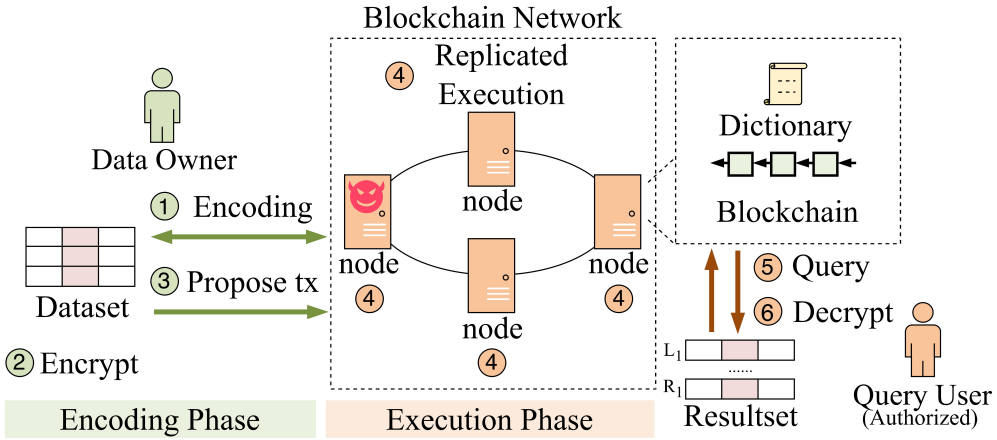




Conventional OPE Schemes

Contributions

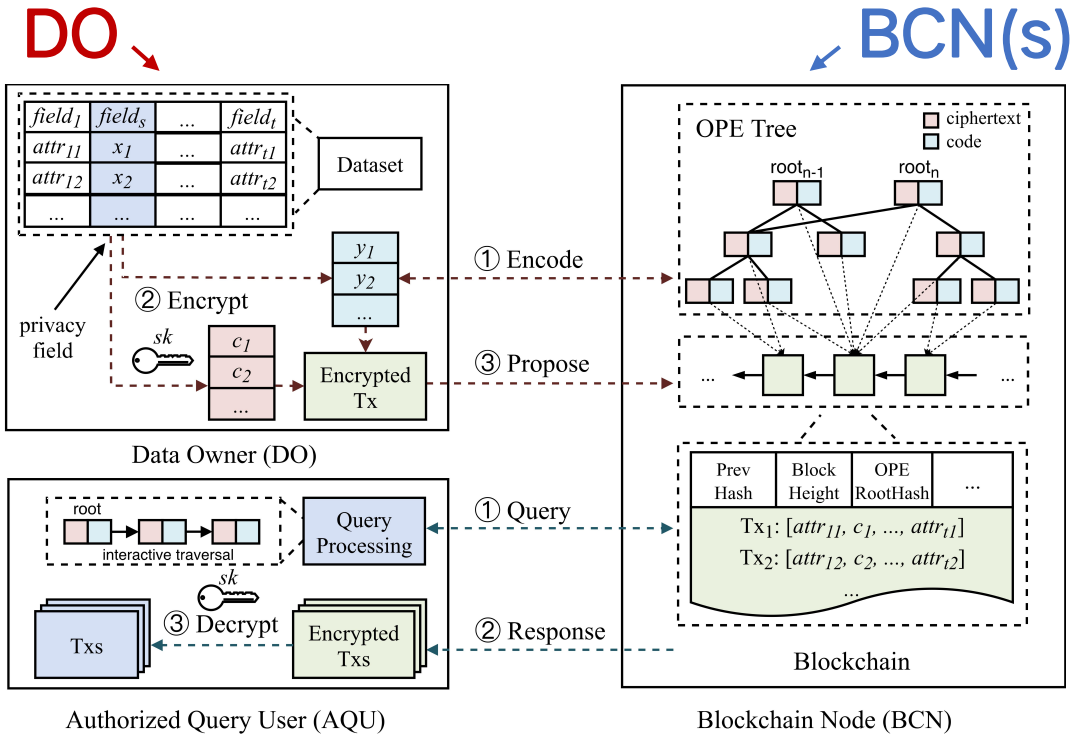
- **BlockOPE**: an efficient OPE scheme towards permissioned blockchain
  - Tech#1: Propose a **novel two-phase scheme** (encoding and execution phase)
  - Tech#2: Optimize the dictionary maintenance with **parallel processing and conflict-reducing** design
  - Tech#3: Leverage an **adaptive cache** 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 ⩾ 3f + 1.

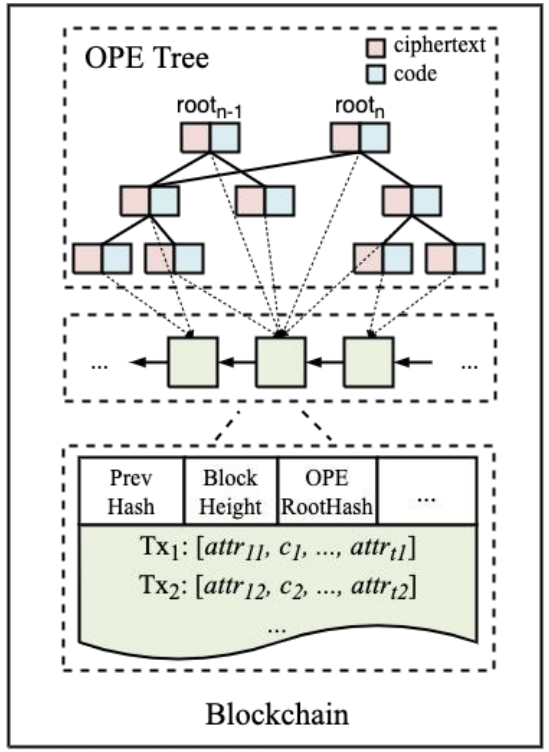


DO, AQU and BCNs of BlockOPE

Methodology

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

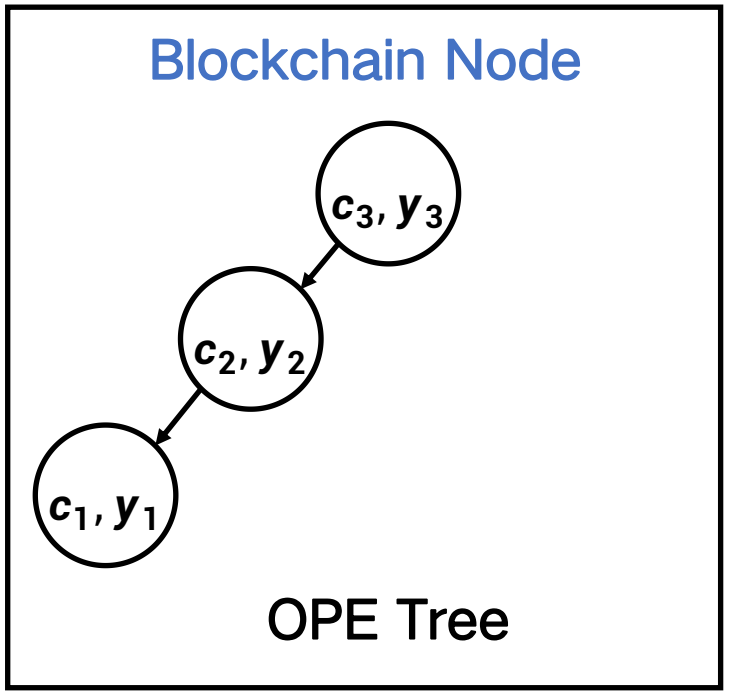
OPE Tree



Blockchain Node (BCN)

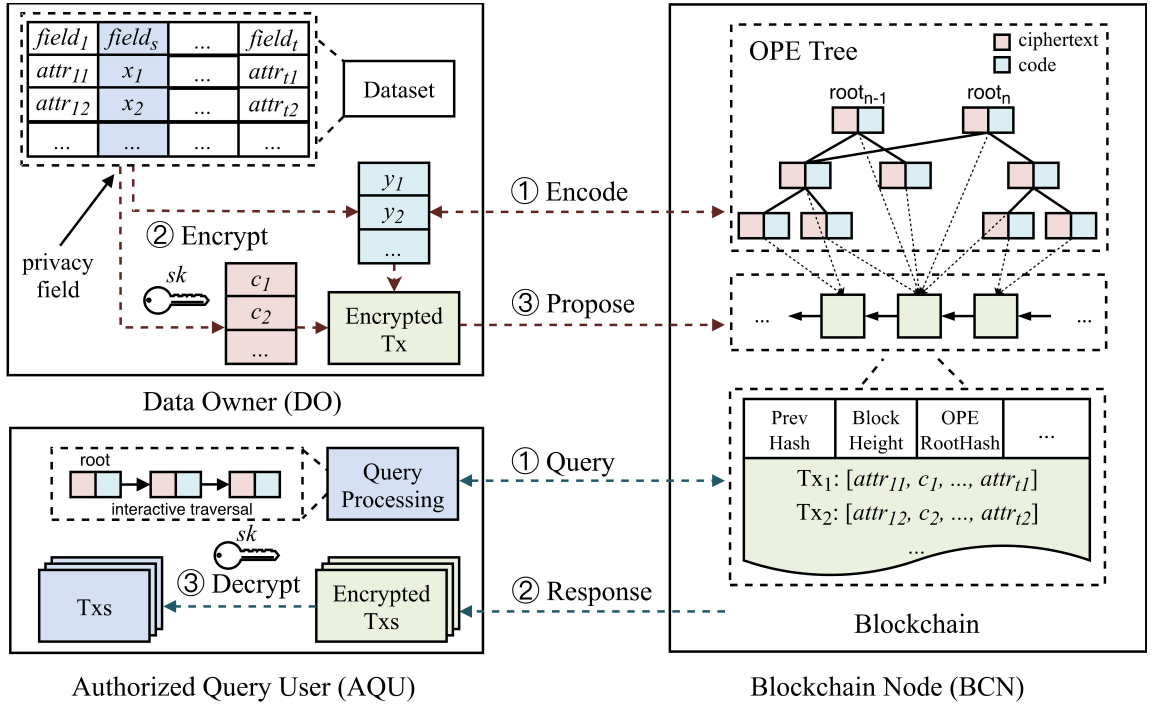
Methodology

- OPE Tree:
  - The OPE Tree is a data structure of a collection of vertices in the form of ⟨c, y⟩. It can be seen as an index structure built on blockchain transactions, meaning each vertex links to its corresponding transaction.
  - *Definition:* The OPE Tree T is a binary search tree consisting of a set of vertices, $\forall$ vertex $v = \langle c,y \rangle \in T$, c = Encrypt(x), y = Encode(x), where x is the plaintext of private data.



Methodology

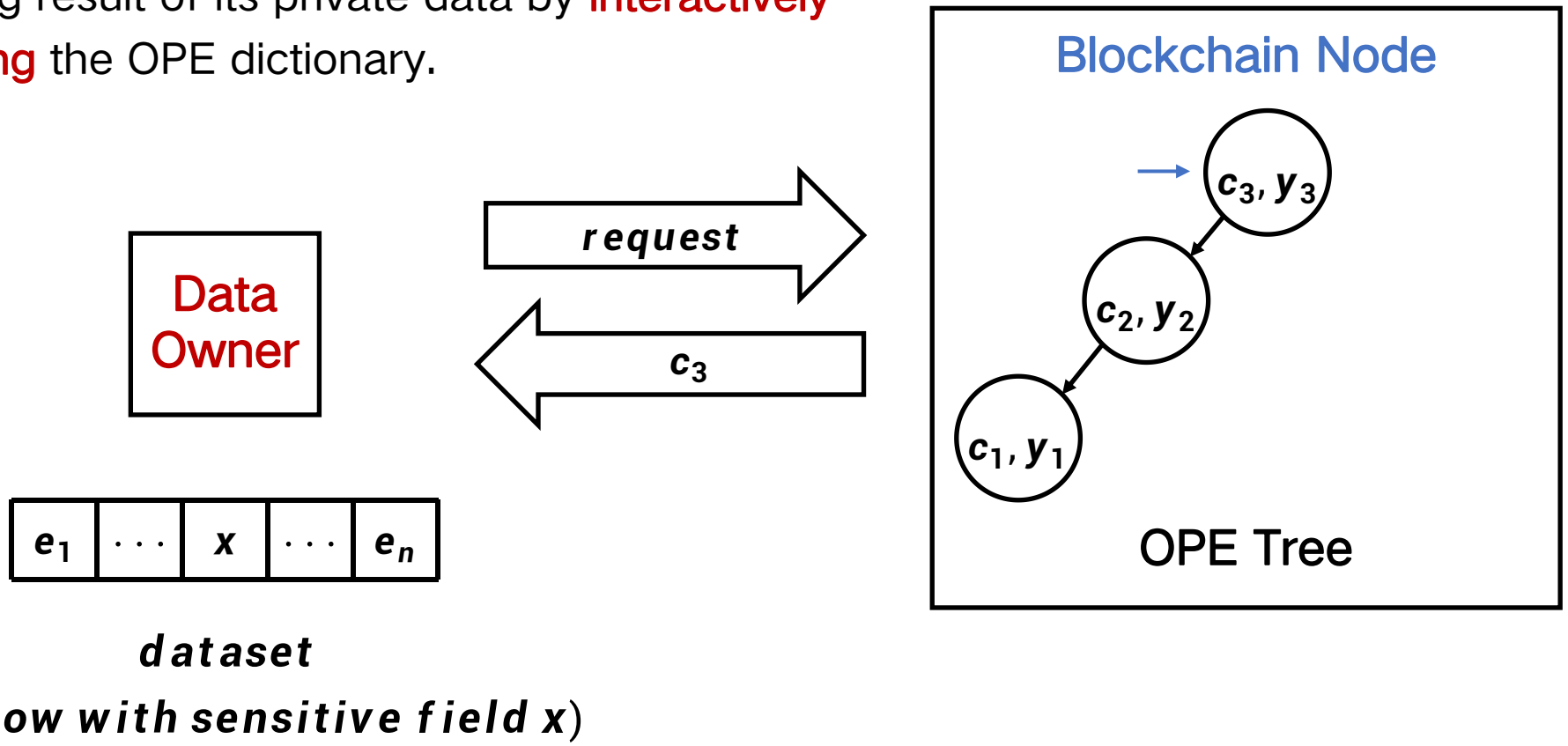
- Serial Two-phase BlockOPE:
  - Encoding Phase
    - DO interacts with BCN(s) to get the encoding result of its private data.
  - Execution Phase
    - DO sends the order-preserved codes to BCN(s) as a transaction.
    - BCNs execute agreed transactions to update the OPE Tree.



Processing of BlockOPE

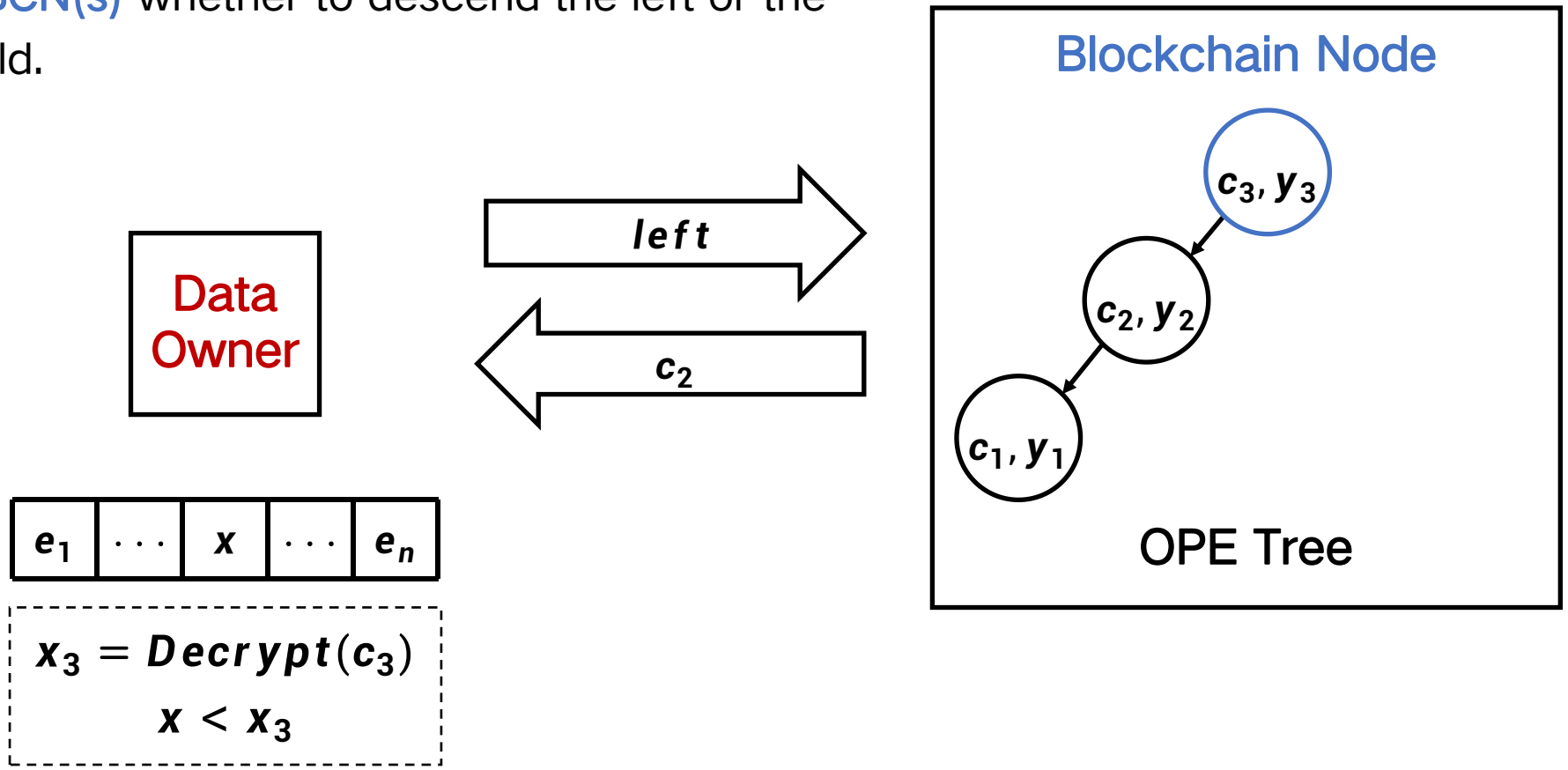
Methodology

- 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.



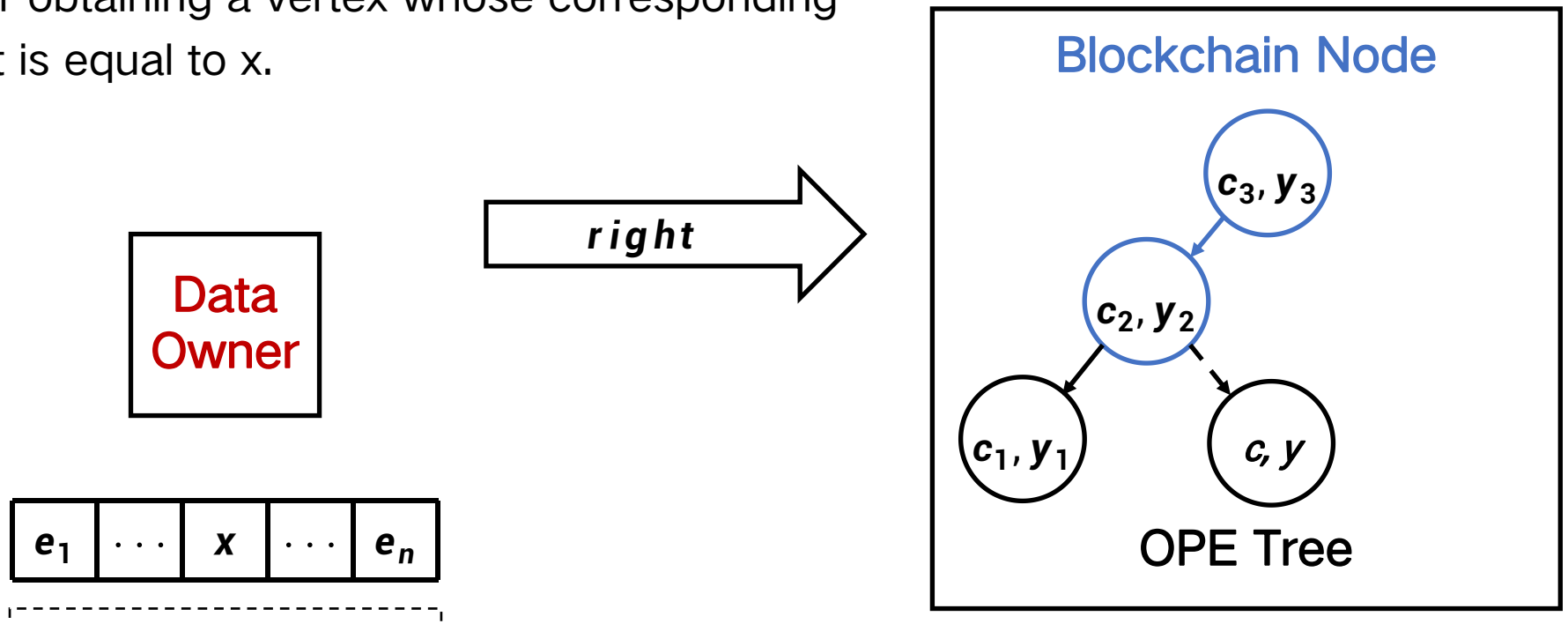
Methodology

- 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.

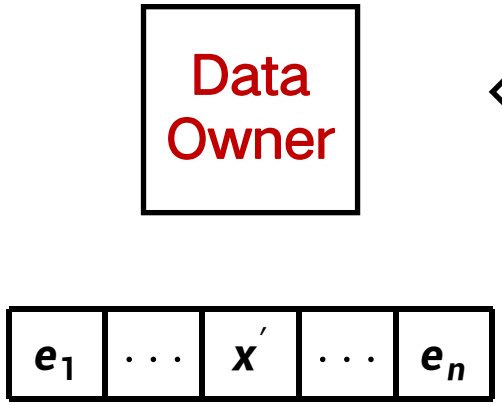


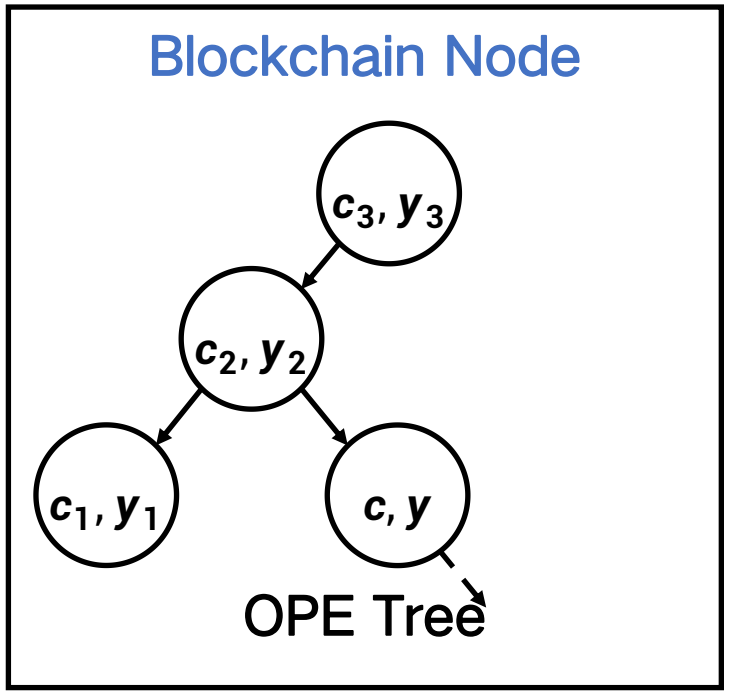
$$x_2 = Decrypt(c_2)$$
$$x > x_2$$

If $y_3 - y_2 > 1$, computes the arithmetic mean of y_3 and y_2 as the **code y**: $y = y_2 + \lceil \frac{y_3 - y_2}{2} \rceil$

Methodology

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

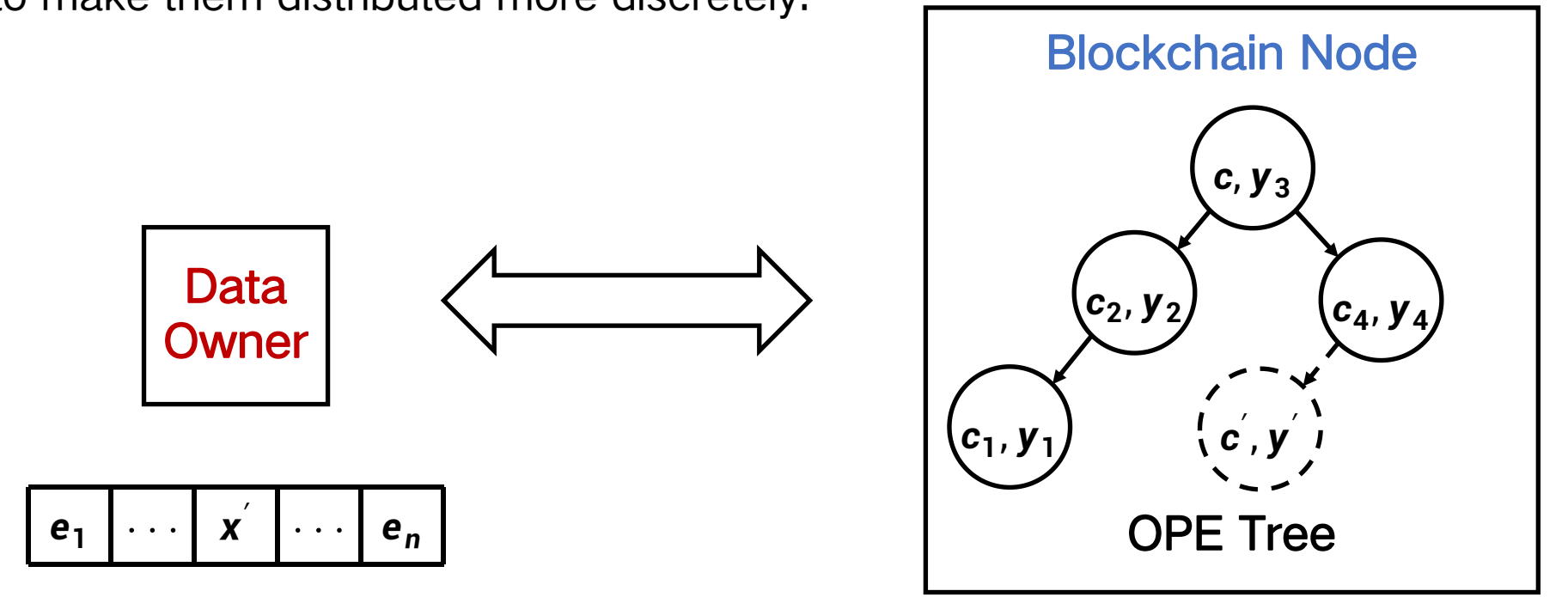




If $y_3 - y_2 = 1$,
the OPE Tree needs to be rebalanced

Methodology

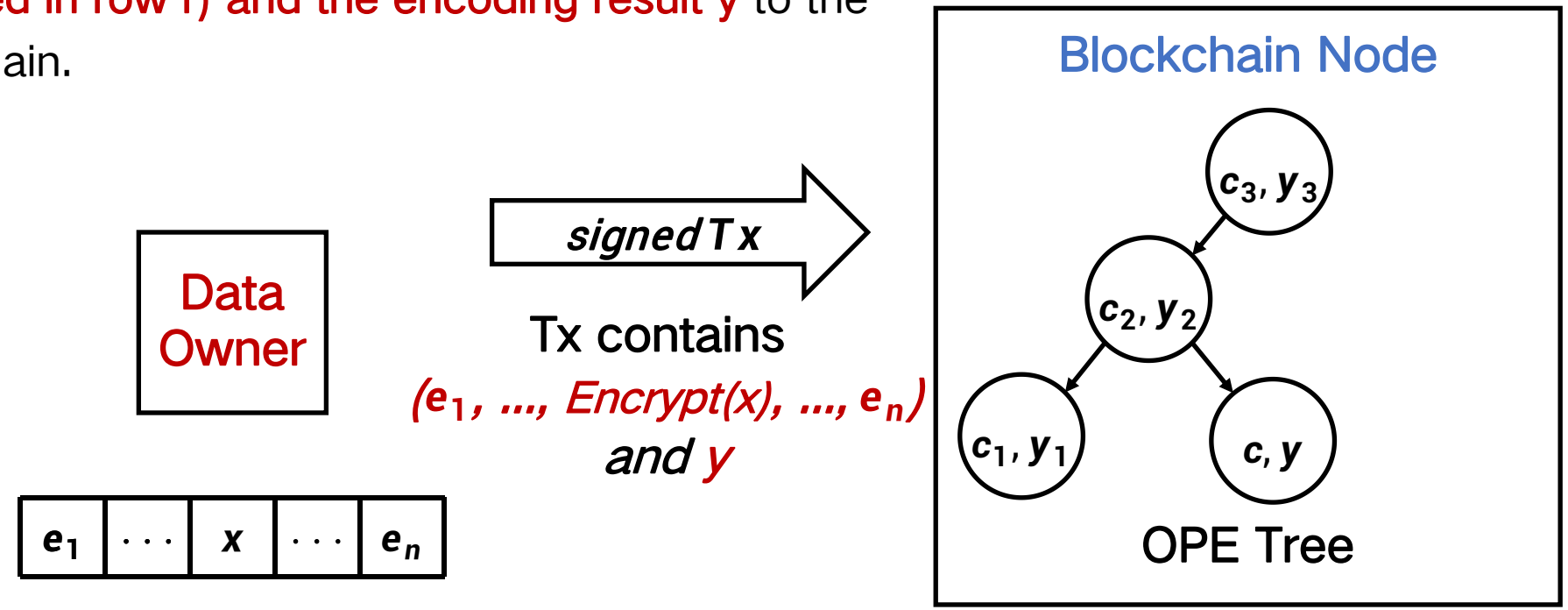
- Encoding Phase:
  - Rebalance of OPE Tree: re-encoded all the existing codes to make them distributed more discretely.



re-encode after tree rebalance

Methodology

- Execution Phase:
  - DO sends a transaction containing the ciphertext c (included in row r) and the encoding result y to the blockchain.

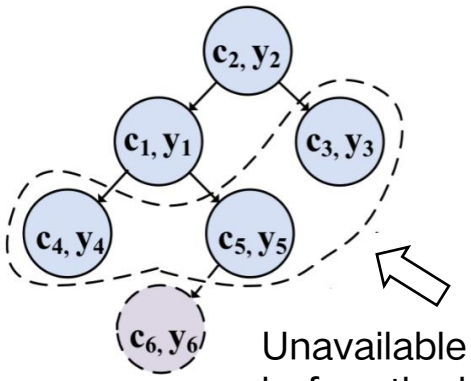


after consensus and replicated execution

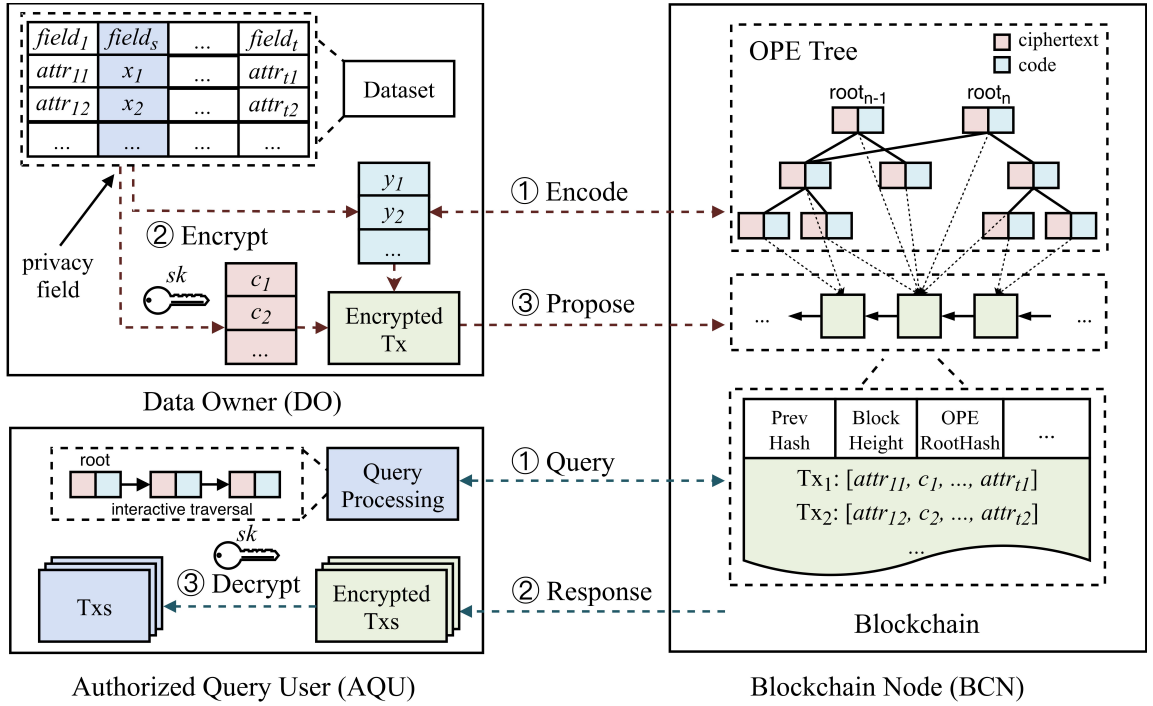
Optimization

- 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**



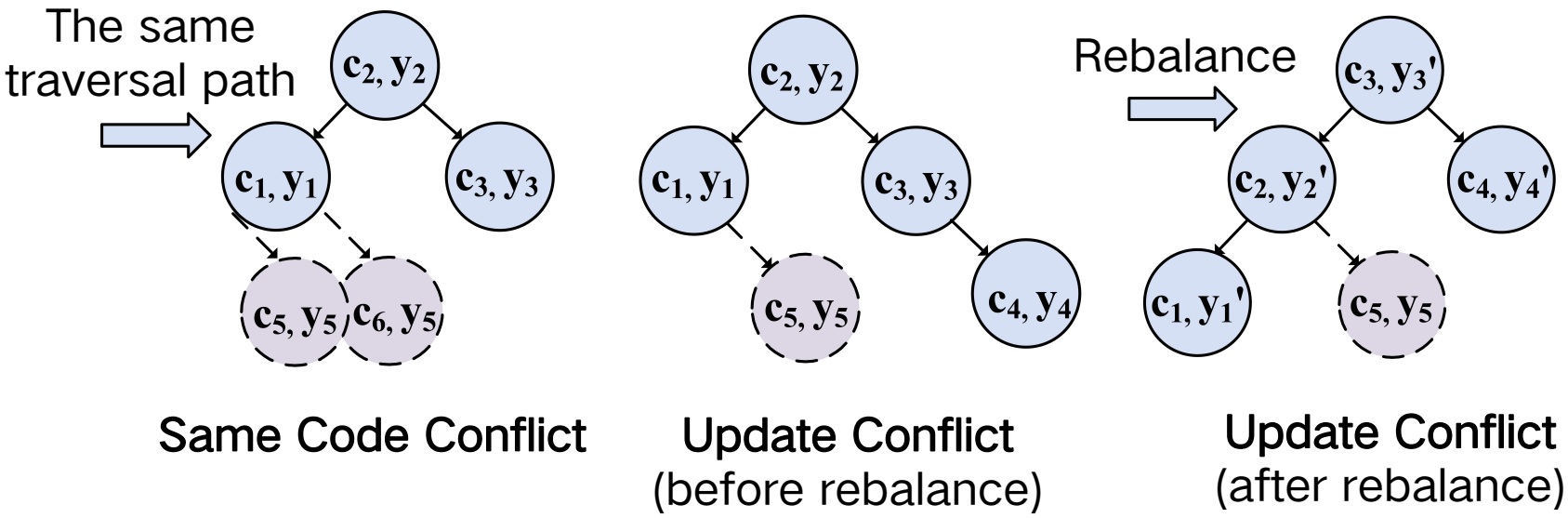
Unavailable for encoding before the block committed



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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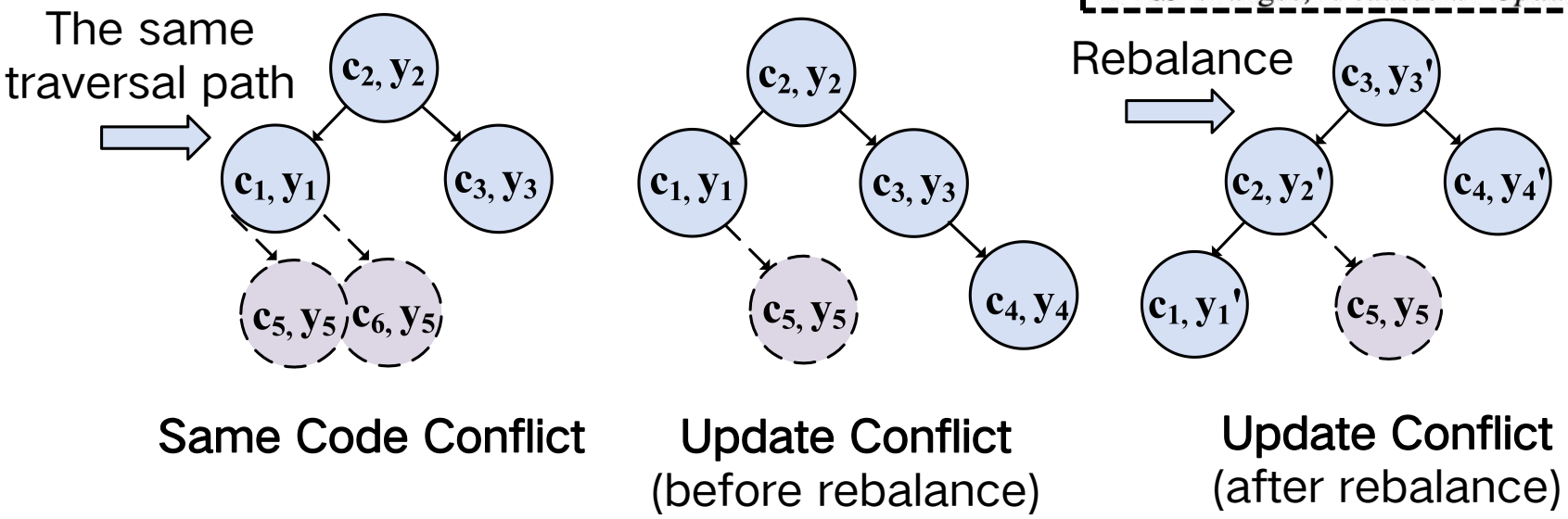
    - **Same Code Conflict(SCC):** multiple encoding requ the same traversal path in the OPE Tree.
    - **Update Conflict (UC):** the OPE Tree is rebalanced

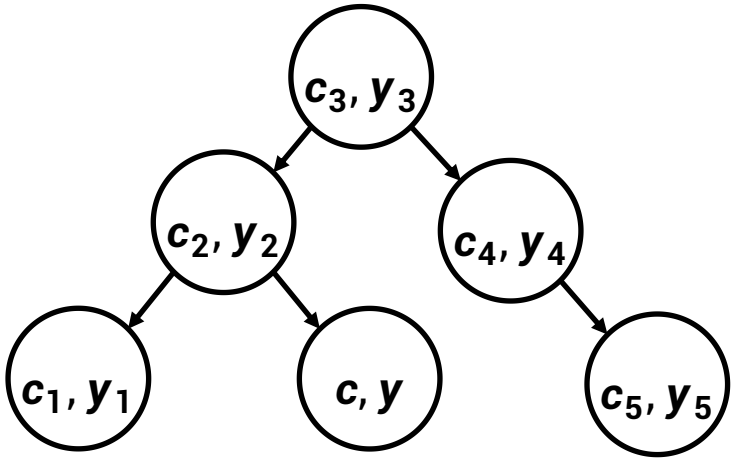
Definition 3: Same Code Conflict (SCC). Given $x_1, x_2 \in \Phi$ and $x_1 \neq x_2$, if $\exists$ mappings $x_1 \rightarrow y$ and $x_2 \rightarrow y$, where $y \in \Upsilon$, it causes a *Same Code Conflict*.

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*.

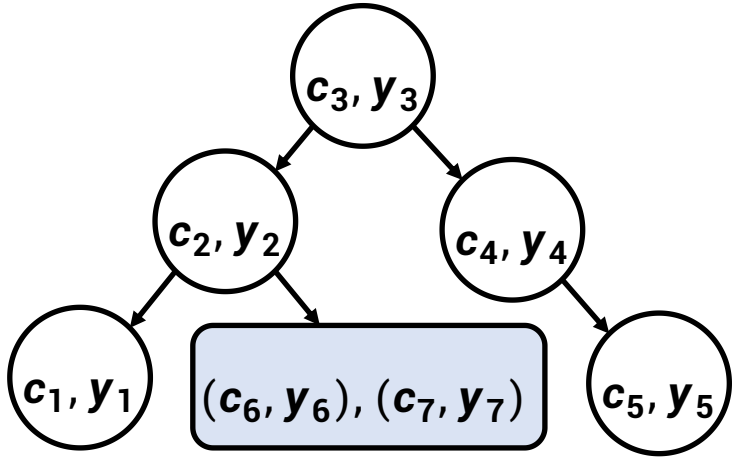


Optimization

- 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.



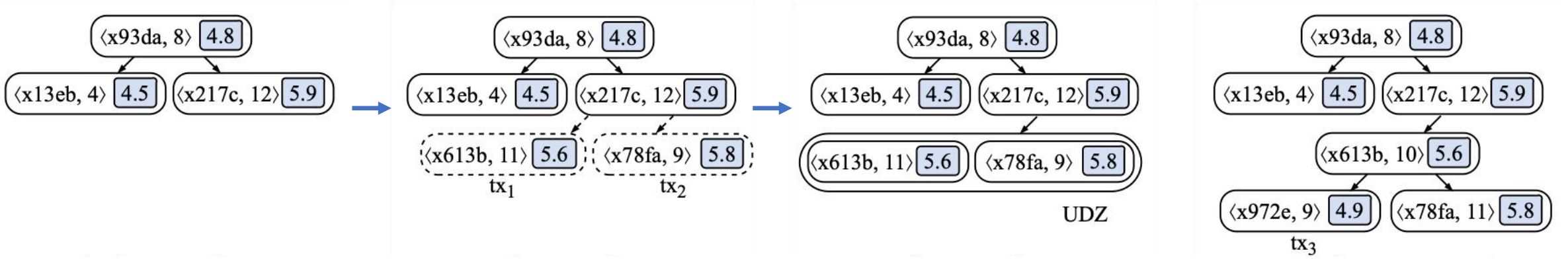
$$y = y_k + \lceil \frac{y_{k+1} - y_k}{2} \rceil + \varepsilon$$



undecided-zone

Optimization

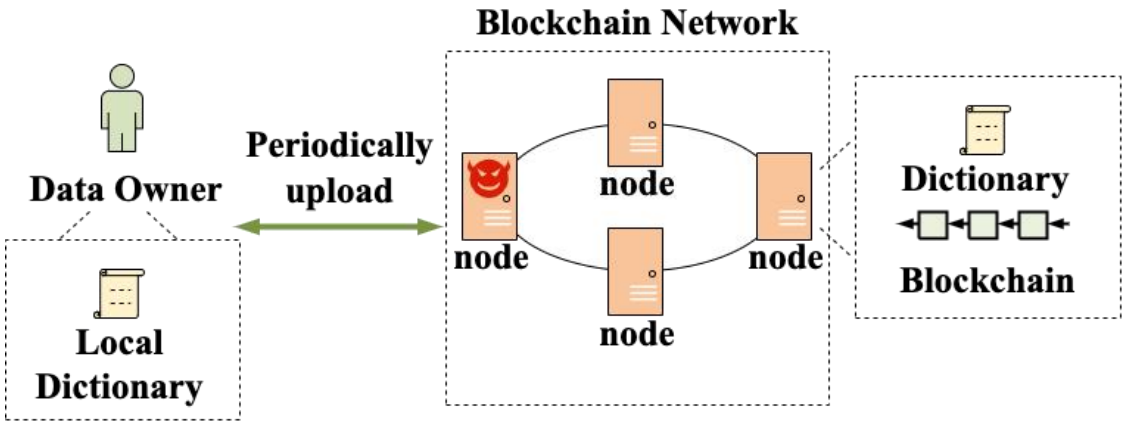
- Reducing Conflicts:
  - Randomized encoding
    - add a noise ε to eliminate the possibility of distinct plaintexts encoded to the same code.
  - Undecided-zone (UDZ) structure
    - a UDZ stores multiple vertices whose codes are non-order-preserving but within a certain range. (implicitly improve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



before encoding | after encoding | after execution | case of rearrangement

Optimization

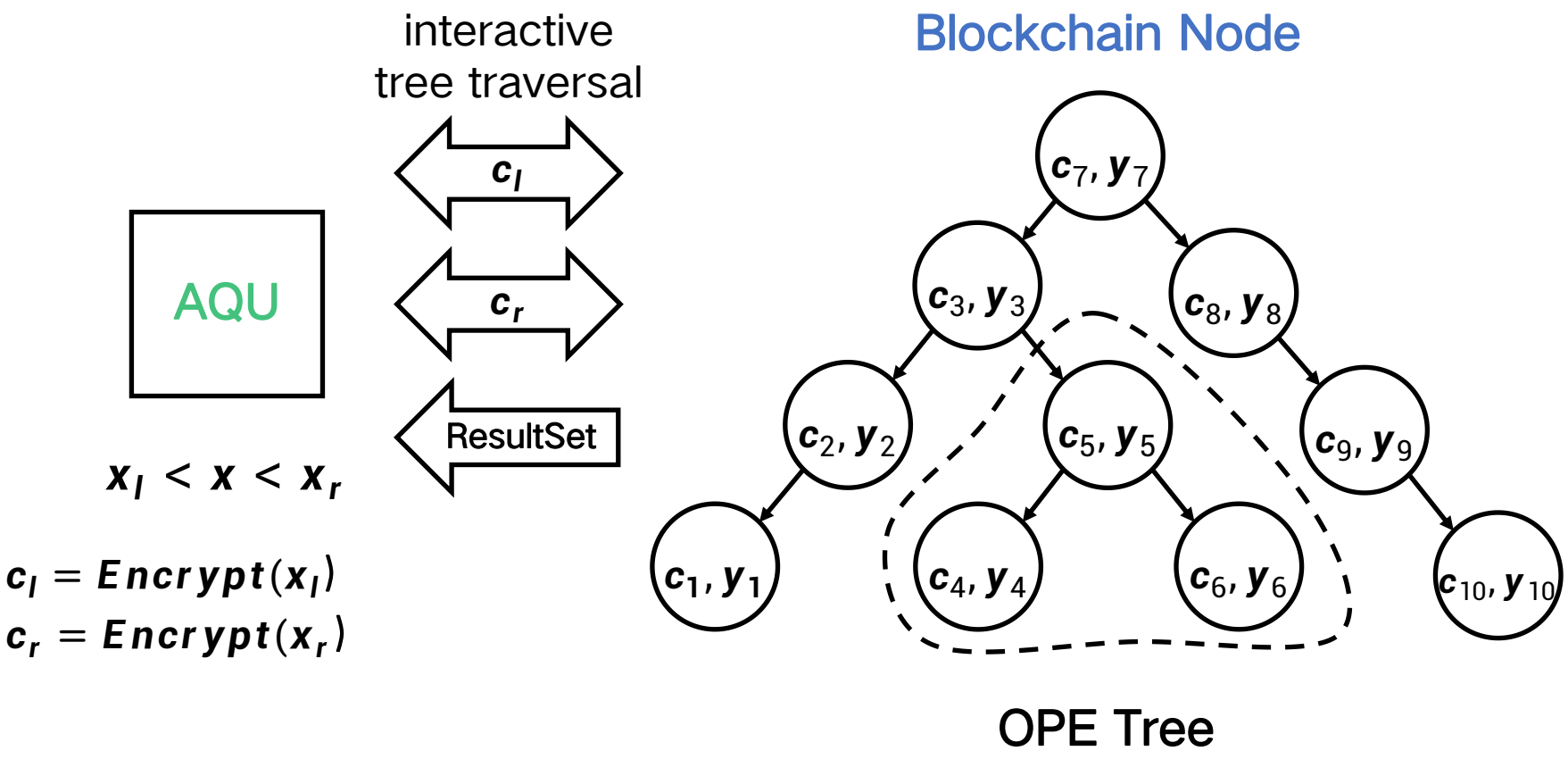
- Local Pre-processing:
  - An optional optimization to accelerate the processing
    - making **trade-offs between conflicts and client storage**.
    - on-chain insertion and resolution play the role of **final guards** to guarantee the correctness of BlockOPE.



Local Pre-processing

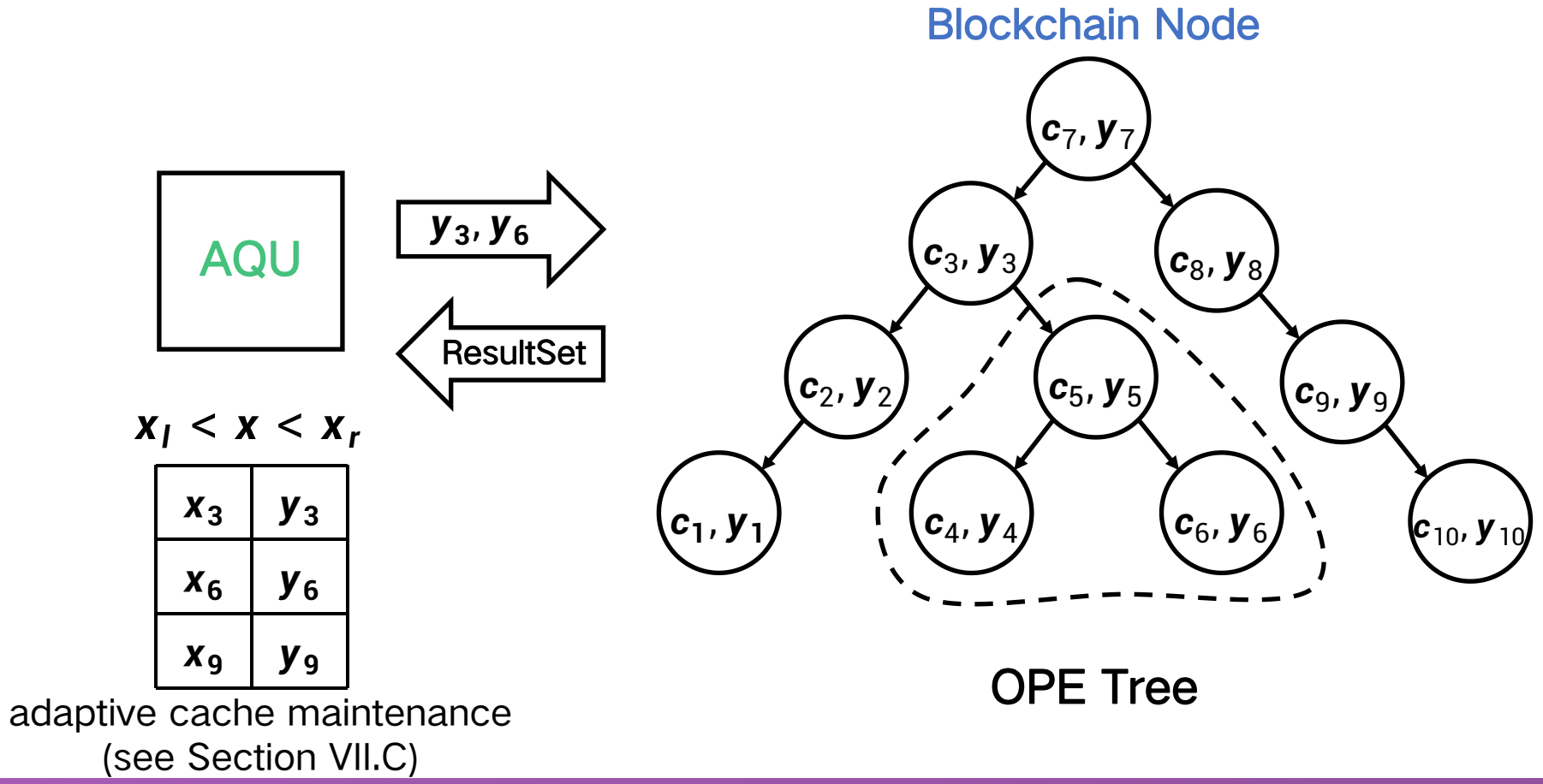
Query Processing

- 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: $S_0 = \{x_1^0, x_2^0, \ldots, x_n^0\}$, $S_1 = \{x_1^1, x_2^1, \ldots, x_n^1\}$,

  $x_i^0 < x_j^0 \Leftrightarrow x_i^1 < x_j^1$. 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.

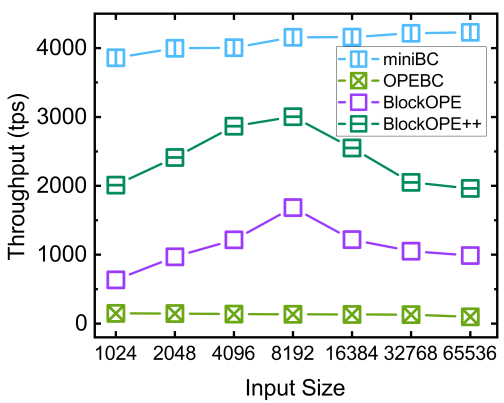
  (see Section VIII.A)

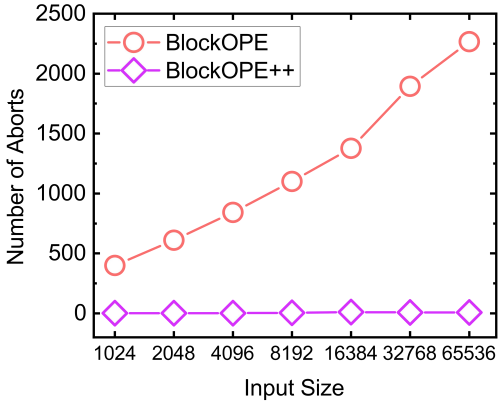
Implementation

- 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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  - Varying input size
  - **Varying block size**
  - Varying number of executing threads
  - Varying UDZ capacity
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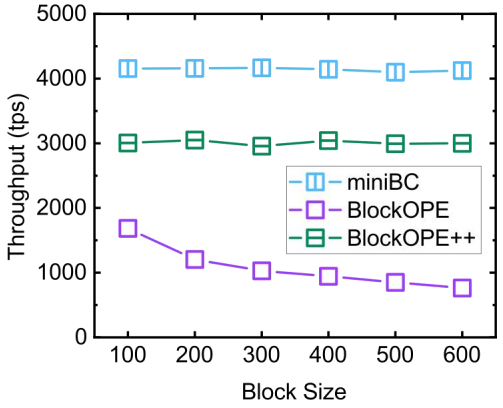

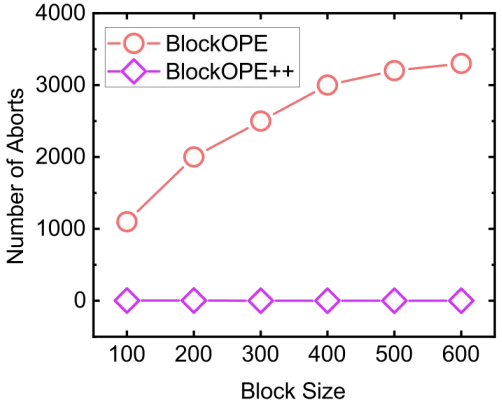

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Experiment

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

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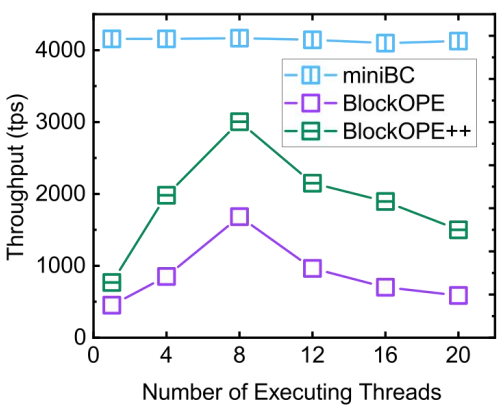
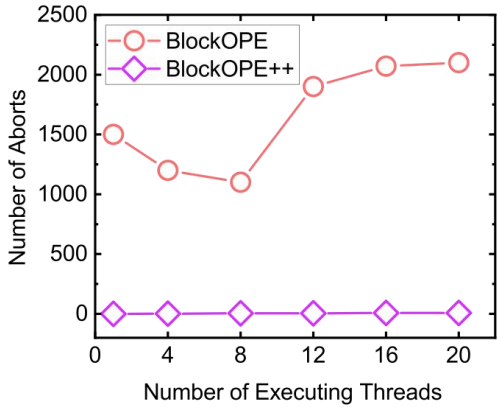
# of exe. threads	1 2 4 8 ...	block size	100 200 ...
UDZ capacity	100 200 ...	distribution	uniform





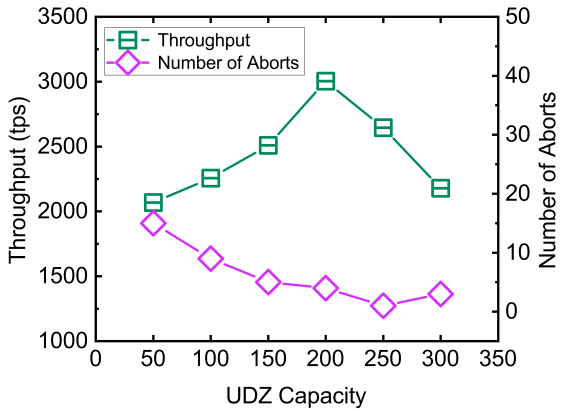
Varying number of executing threads

Experiment

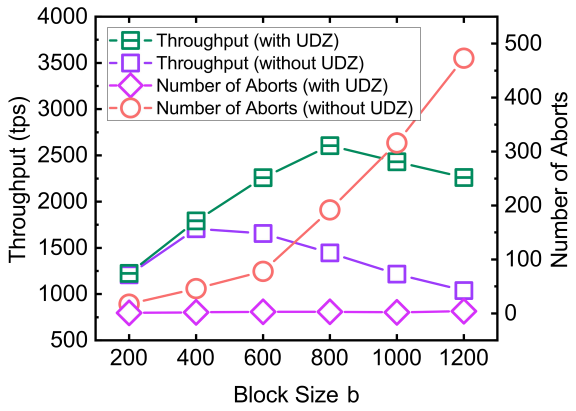
- Performance Evaluation
  - Varying input size
  - Varying block size
  - Varying number of executing threads
  - **Varying UDZ capacity**
  - **Evaluation of Conflict Reduction**

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



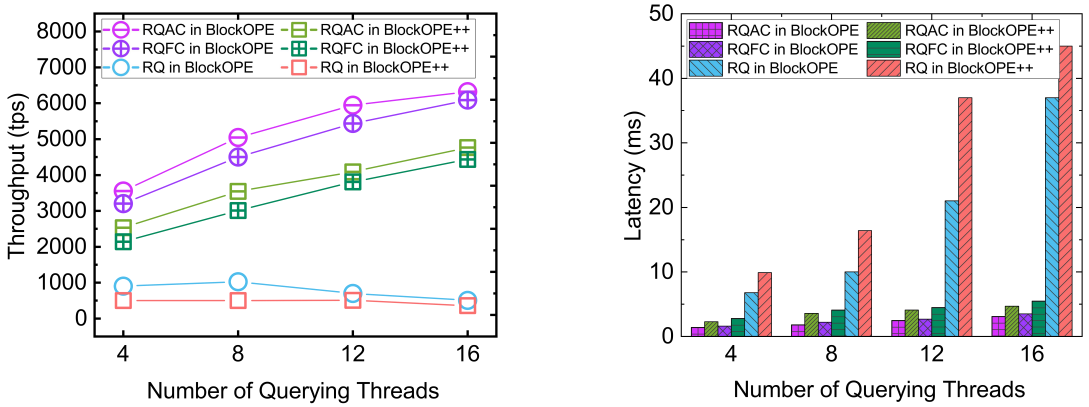
Varying UDZ capacity



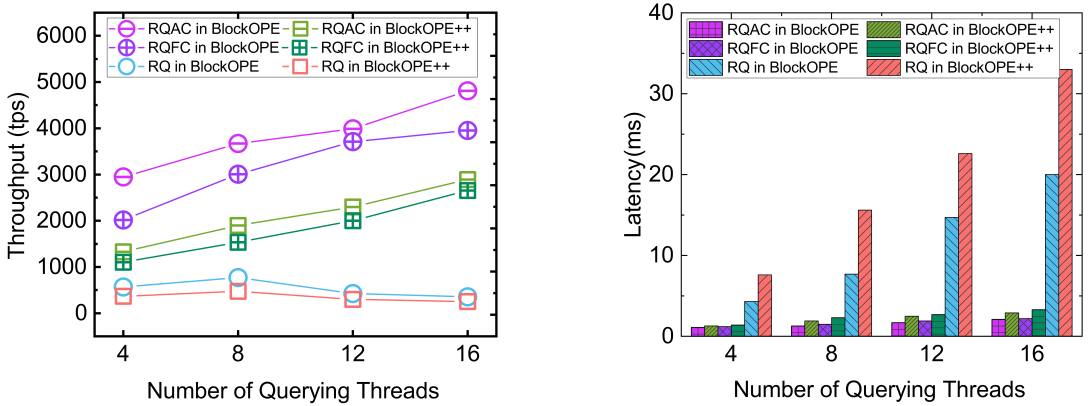
Evaluation of Conflict Reduction

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 !