vChain: Enabling Verifiable Boolean Range Queries over Blockchain Databases

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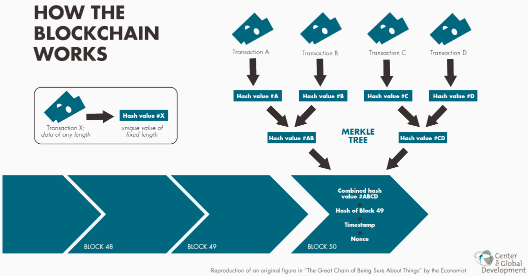
Background

- Blockchain: Append-only data structure collectively maintained by a network of (untrusted) nodes
  - Hash chain
  - Consensus
  - Immutability
  - Decentralization



Blockchain Structure *[Credit: Wikipedia]*

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  - Hash chain
  - Consensus
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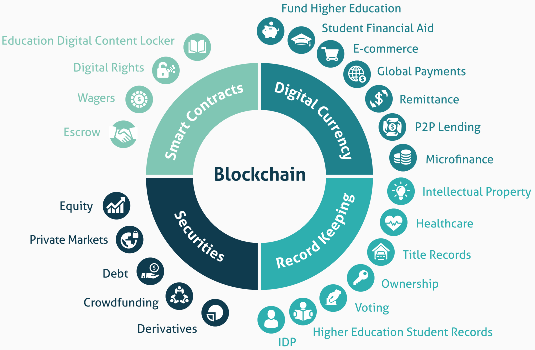
  - Decentralization
- A wide range of applications
  - Digital identities
  - Decentralized notary
  - Distributed storage
  - Smart Contracts
  - . . .



Blockchain Applications *[Credit: FAHM Technology Partners]*

Blockchain Database Solutions

- Increasing demand to search the data stored in blockchains
- Blockchain database solutions to support SQL-like queries

SwarmDB

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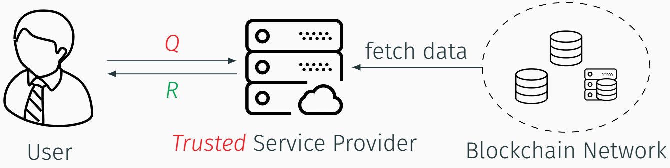

Workflow of Existing Solutions

- **Issue**: relying on a trusted party who can faithfully answer user queries

Secure Blockchain Search

- The assumption of trusted party may not always hold

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- Basic solution to integrity-assured blockchain search
  - Becoming full node
  - High cost
    - Storage: to store a complete replicate (240 GB for Bitcoin as of June 2019)
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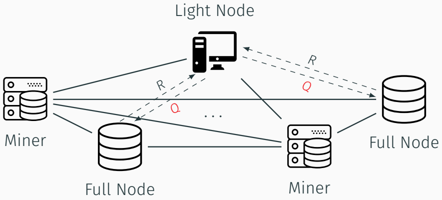

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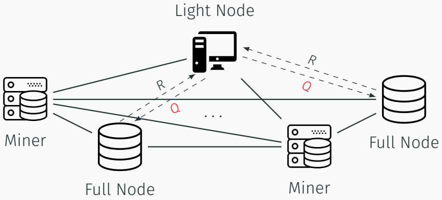

- Challenge: how to maintain query integrity?

Solution #1: Smart Contract

- A trusted program to execute user-defined computation upon the blockchain
  - Smart Contract reads and writes blockchain data
  - Execution integrity is ensured by the consensus protocol
- Offer trusted storage and computation capabilities
- Function as a trusted virtual machine

	Traditional Computer	Blockchain VM
Storage	RAM	Blockchain
Computation	CPU	Smart Contract

Solution #1: Smart Contract

- Leverage Smart Contract for trusted computation
  - Users submit query parameters to blockchain
  - Miners execute computation and write results into blockchain
  - Users read results from blockchain

[Credit: Oscar W]

S. Hu, C. Cai, Q. Wang, C. Wang, X. Luo, and K. Ren, "Searching an encrypted cloud meets blockchain: A decentralized, reliable and fair realization," in *IEEE INFOCOM*, Honolulu, HI, USA, 2018, pp. 792–800.

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- Drawbacks
  - Long latency: long time for consensus protocol to confirm a block
  - Poor scalability: transaction rate of the blockchain is limited
  - Privacy concern: query history is permanently and publicly stored in blockchain
  - High cost: executing smart contract in ETH requires paying gas to miners
    (*INFOCOM 2018 requires* 4 201 232 *gas* = 0.18 *Ether* = 24 *USD per query*)

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    - Service provider returns results with cryptographic proof
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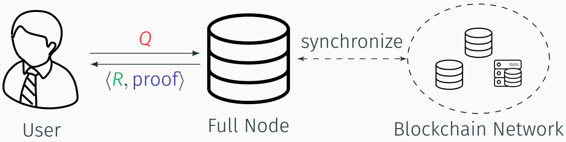
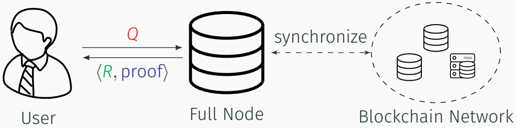
- Outsource queries to full node and verify the results using VC
  - General VC: Expressive but high overhead
  - Authenticated Data Structure (ADS)-based VC: Efficient but requiring customized designs



vChain

Our Solution: vChain

- **Problem**: Integrity-assured Search over Blockchain Data



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  - Users become light nodes
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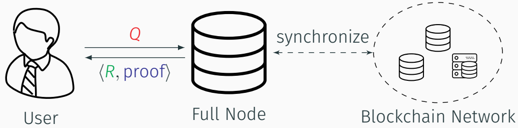

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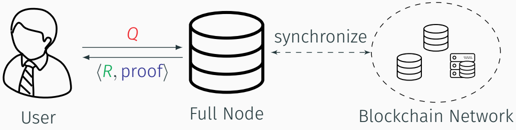
  - Program glitches
  - Security vulnerabilities
  - Commercial interest
  - ...



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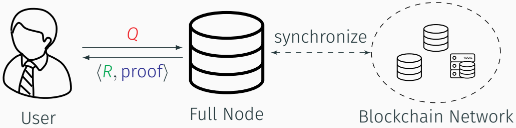

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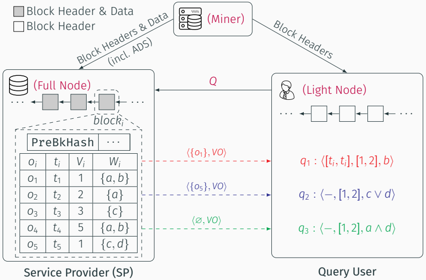
- Security requirements
  - Soundness: none of the objects returned as results have been tampered with and all of them satisfy the query conditions
  - Completeness: no valid result is missing regarding the query conditions

vChain — System Overview

- **Miner**: constructs each block with additional ADS to achieve VC scheme
- **Service Provider**: is a full node and computes the results with the verification object (VO)
- **Query User**: is a light node; uses the VO and block header to verify the results



System Model of vChain

vChain — Data Model & Queries

- Data Model
  - Each block contains several temporal objects $\{o_1, o_2, \ldots, o_n\}$
  - o_i is represented by $\langle t_i, V_i, W_i \rangle$
    (*timestamp, multi-dimensional vector, set valued attribute*)

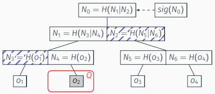
- Boolean Range Queries
  - Find all Bitcoin transactions happening in certain period
    Tx: $\langle$time, transfer amount, {"send address", "receive address"}$\rangle$
    $q = \langle [2018\text{-}05, 2018\text{-}06], [10, +\infty], \text{"send:1FFYc"} \wedge \text{"receive:2DAAf"} \rangle$
  - Subscribe to car rental messages with certain price and keywords
    Tx: $\langle$time, rental price, {"type", "model"}$\rangle$
    $q = \langle -, [200, 250], \text{"Sedan"} \wedge (\text{"Benz"} \vee \text{"BMW"}) \rangle$

Challenges

- How to construct ADS for unbounded and append-only blockchain data?
- How to design a one-size-fits-all ADS scheme that supports dynamic queries over arbitrary attributes?
- How to leverage intra/inter-block optimization techniques to improve query efficiency?
- How to make the system highly scalable to a large number of subscription queries?

Cryptographic Building Block

- **Merkle Hash Tree** [Mer89]
  - Support efficient membership/range queries
  - Limitations
    - An MHT supports only the query keys on which the Merkle tree is built
    - MHTs do not work with set-valued attributes
    - MHTs of different blocks cannot be aggregated



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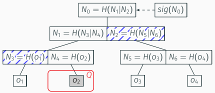

Merkle Hash Tree

- **Cryptographic Multiset Accumulator** [PTT11]
  - Map a multiset to an element in cyclic multiplicative group in a collision resistant fashion
  - Utility: prove set disjoint
  - Protcols:
    - $\text{KeyGen}(1^\lambda) \rightarrow (sk, pk)$: generate keys
    - $\text{Setup}(X, pk) \rightarrow \text{acc}(X)$: return the accumulative value w.r.t. X
    - $\text{ProveDisjoint}(X_1, X_2, pk) \rightarrow \pi$:
      on input two multisets X_1 and X_2, where $X_1 \cap X_2 = \emptyset$, output a proof π
    - $\text{VerifyDisjoint}(\text{acc}(X_1), \text{acc}(X_2), \pi, pk) \rightarrow \{0, 1\}$:
      on input the accumulative values $\text{acc}(X_1)$, $\text{acc}(X_2)$, and a proof π, output 1 iff $X_1 \cap X_2 = \emptyset$

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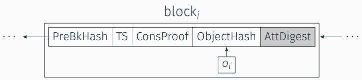
  - Extend the block header with *AttDigest*
  - $AttDigest = acc(W_i) = \mathrm{Setup}(W_i, pk)$
    - Constant size regardless of number of elements in W_i
    - Support ProveDisjoint$(\cdot)$ & VerifyDisjoint$(\cdot)$



Extended Block Structure

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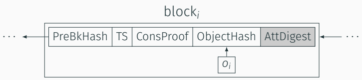
  - Match:
  - Mismatch:



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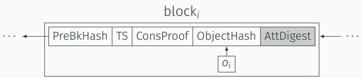

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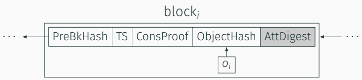

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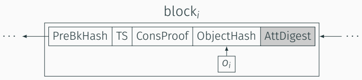


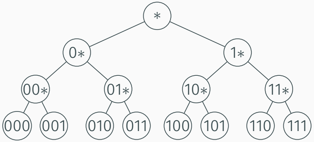
Extended Block Structure

Example of Mismatch

- Transform query condition to a list of sets: $q = \text{“Sedan”} \wedge (\text{“Benz”} \vee \text{“BMW”}) \rightarrow \{\text{“Sedan”}\}, \{\text{“Benz”}, \text{“BMW”}\}$
- Consider $o_i : \{\text{“Van”}, \text{“Benz”}\}$, we have $\{\text{“Sedan”}\} \cap \{\text{“Van”}, \text{“Benz”}\} = \varnothing$
- Apply ProveDisjoint($\{\text{“Van”}, \text{“Benz”}\}, \{\text{“Sedan”}\}, pk$) to compute proof π
- User retrieves $AttDigest = acc(\{\text{“Van”}, \text{“Benz”}\})$ from the block header and uses VerifyDisjoint($AttDigest$, $acc(\{\text{“Sedan”}\})$, π, pk) to verify the mismatch

Extension to Range Queries

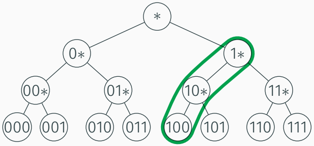
- Idea: transform numerical attributes into set-valued attributes



Example of Transformation

Extension to Range Queries

- **Idea**: transform numerical attributes into set-valued attributes
- Numerical value can be transformed into a set of binary prefix elements
  - Example: $\text{trans}(4) = \{1*, 10*, 100\}$
    * denotes wildcard matching operator



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  - Example: $[0, 6] \rightarrow 0* \vee 10* \vee 110$
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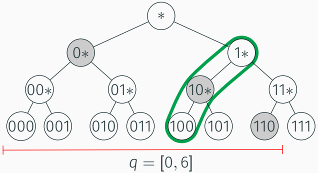

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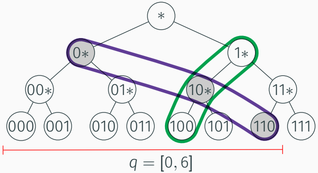

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- Range queries can be processed in a similar manner as boolean queries
  - Transform $v_i \in [\alpha, \beta] \rightarrow \text{trans}(v_i) \cap \text{EquiSet}([\alpha, \beta]) \neq \varnothing$
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    - $4 \in [0, 6] \rightarrow \{1*, 10*, 100\} \cap \{0*, 10*, 110\} = \{10*\} \neq \varnothing$

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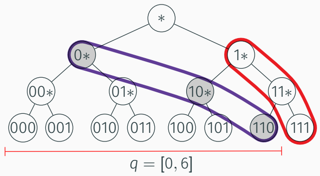

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    - $7 \notin [0, 6] \rightarrow \{1*, 11*, 111\} \cap \{0*, 10*, 110\} = \varnothing$

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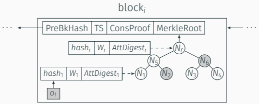

Node	Object	Set Attributes
N_1	o_1	$W_1 = \{$"Sedan", "Benz"$\}$
N_2	o_2	$W_2 = \{$"Sedan", "Audi"$\}$
N_3	o_3	$W_3 = \{$"Van", "Benz"$\}$
N_4	o_4	$W_4 = \{$"Van", "BMW"$\}$

Intra-Block Index

Batch Verification & Subscription Queries

- **Observation**: objects may share common attributes that mismatch query condition
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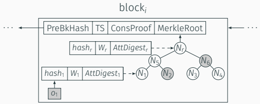
  - **Inter-Block Index**: aggregate objects across blocks using skip list



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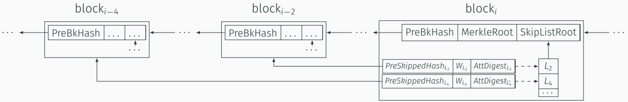
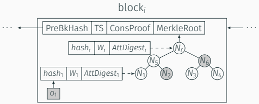


Inter-Block Index

Batch Verification & Subscription Queries

- Observation: objects may share common attributes that mismatch query condition
- Idea: we can aggregate them to speed up query processing
  - Intra-Block Index: aggregate objects inside same block using MHT
  - Inter-Block Index: aggregate objects across blocks using skip list
  - Inverted Prefix Tree: aggregate similar subscription queries from users



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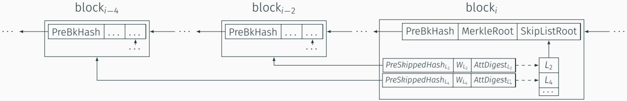
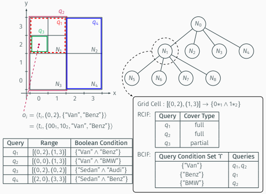


Inter-Block Index



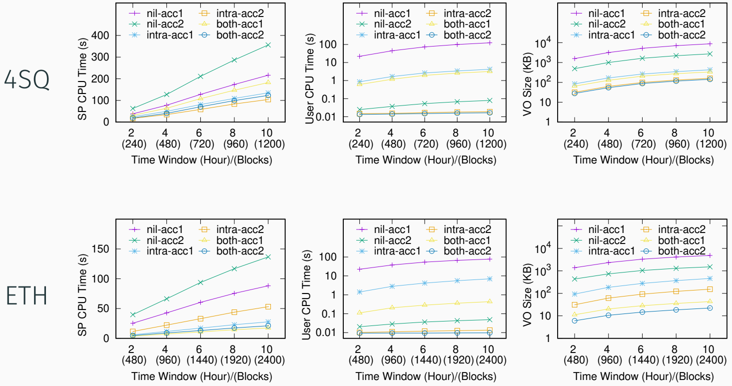
Query	Range	Boolean Condition
q_1	$[(0,2),(1,3)]$	$\{$"Van" $\wedge$ "Benz"$\}$
q_2	$[(0,0),(1,3)]$	$\{$"Van" $\wedge$ "BMW"$\}$
q_3	$[(0,2),(0,2)]$	$\{$"Sedan" $\wedge$ "Audi"$\}$
q_4	$[(2,0),(3,3)]$	$\{$"Sedan" $\wedge$ "Benz"$\}$

Query	Cover Type
q_1	full
q_2	full
q_3	partial

Query Condition Set Υ	Queries
$\{$"Van"$\}$	q_1, q_2
$\{$"Benz"$\}$	q_1
$\{$"BMW"$\}$	q_2

Inverted Prefix Tree

- Evaluation metrics
  - Query processing cost in terms of SP CPU time
  - Query verification cost in terms of user CPU time
  - Size of the VO transmitted from the SP to the user
- Numerical range selectivity
  - 10% for 4SQ
  - 50% for ETH
- Disjunctive Boolean function size
  - 3 for 4SQ
  - 9 for ETH



Time-Window Query Performance

Thanks

Questions?

References

[HCW+18] S. Hu, C. Cai, Q. Wang, C. Wang, X. Luo, and K. Ren, "Searching an encrypted cloud meets blockchain: A decentralized, reliable and fair realization," in *IEEE INFOCOM*, Honolulu, HI, USA, 2018, pp. 792–800.

[ICDE19] C. Zhang, C. Xu, J. Xu, Y. Tang, and B. Choi, "GEM^2-Tree: A gas-efficient structure for authenticated range queries in blockchain," in *IEEE ICDE*, Macau SAR, China, 2019.

[Mer89] R. C. Merkle, "A certified digital signature," in *CRYPTO*, 1989, pp. 218–238.

[PTT11] C. Papamanthou, R. Tamassia, and N. Triandopoulos, "Optimal verification of operations on dynamic sets," in *CRYPTO*, Santa Barbara, CA, USA, 2011, pp. 91–110.

[SIGMOD19] C. Xu, C. Zhang, and J. Xu, "vChain: Enabling verifiable boolean range queries over blockchain databases," in *ACM SIGMOD*, Amsterdam, Netherlands, 2019.