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Scalable Verification for Outsourced Dynamic Databases

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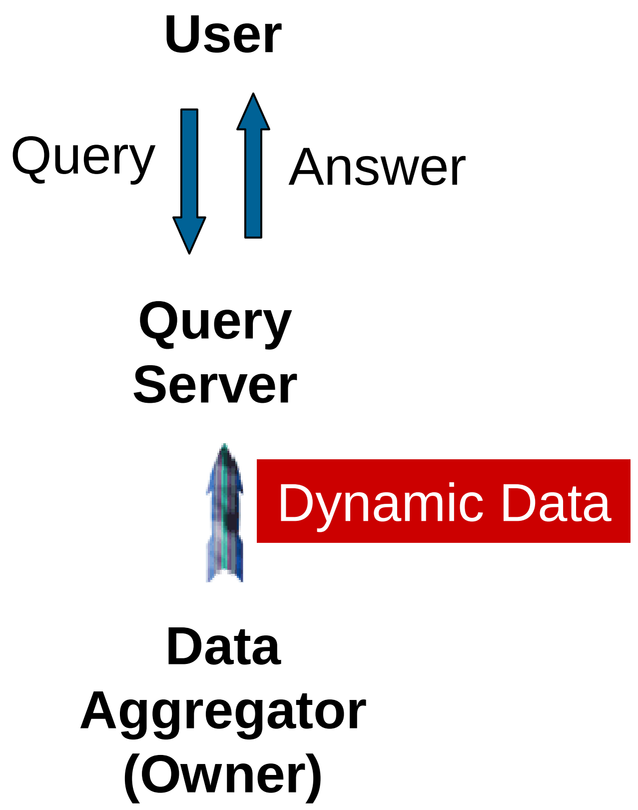
VLDB 2009

What is the Problem?



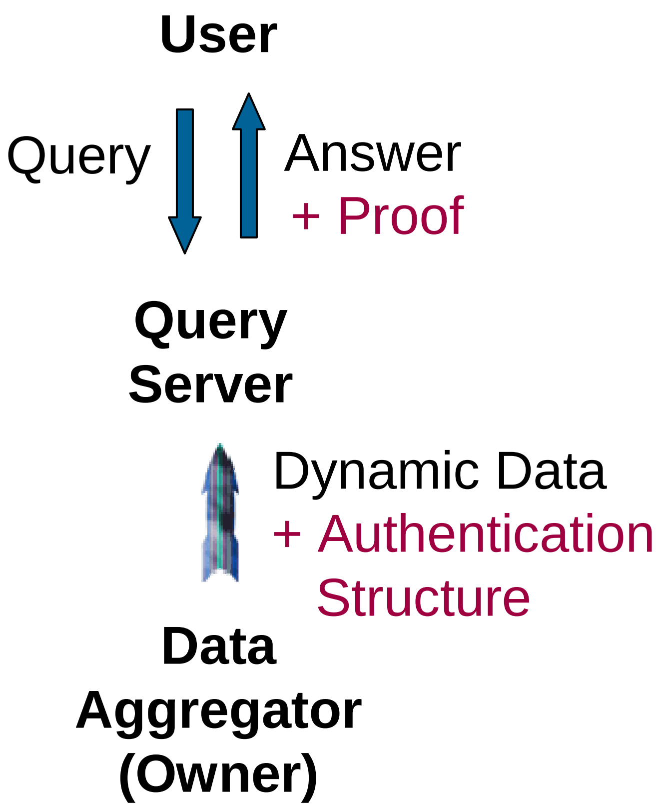
System Model

- Data Aggregator outsources query processing function to the Query Server

Threat Model

- User trusts the Data Aggregator
- Query Server is not untrusted
  - Compromised by hackers
  - Insider attack

Is the Query Answer *"Correct"*?



- Authenticity

  Every value in the answer originated from the Data Aggregator

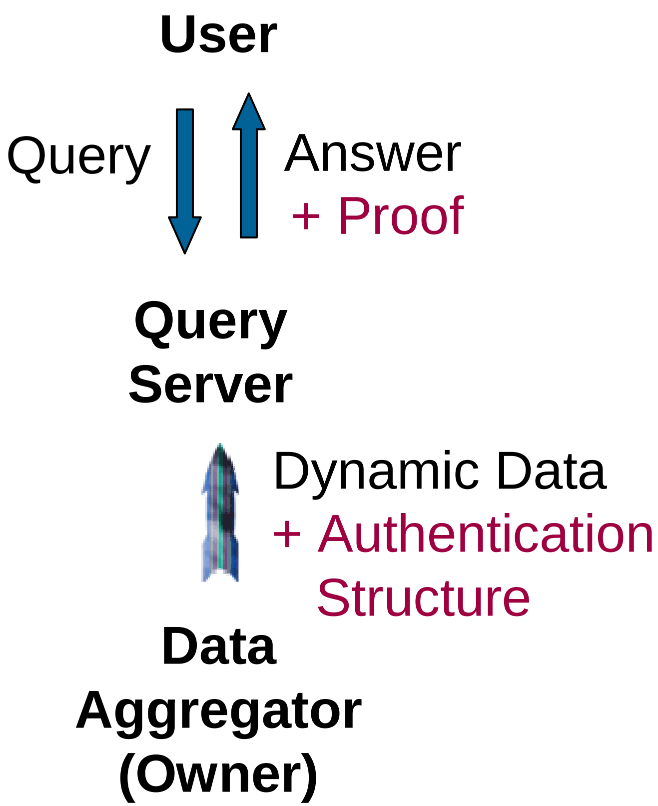
- Completeness

  Every record the satisfies the query condition is in the answer

- ***Freshness***

  The record values in the answer are up-to-date

Authentication Approaches



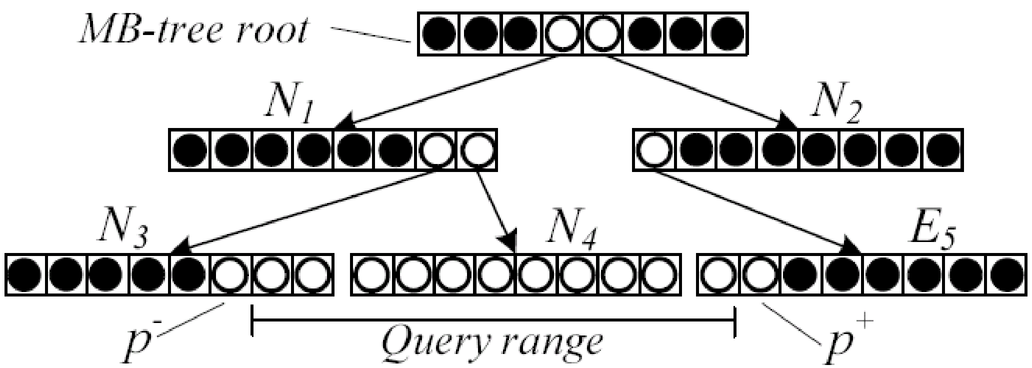
<u>Merkle Hash Tree (MHT)</u>

- Merkle, Crypto 2008
- Devanbu et al, JCS 2003
- Nuckolls et al, DBSec 2005
- Li et al, SIGMOD 2006
- Papadopoulos et al, VLDB 2007
- Goodrich et al, CT-RSA 2008
- …

<u>Signature Aggregation</u>

- Boneh et al, CryptoBytes 2003
- Pang et al, SIGMOD 2005
- Narasimha et al, ACM TOS 2006
- Cheng et al, DBSec 2006
- …

Merkle Hash Tree Approach



(from Li et al, SIGMOD 2006)

Structure

- Embed authentication information in data index
- Node digest is a hash function on node content
- Root digest is certified

Response to query

- Answer = records within query range
- Proof = ● digests along left & right boundaries

User verification

- Compute the ○ digests from records in the answer
- Check ○○○ … + ●●● … = certified root?

Limitations of MHT Approach

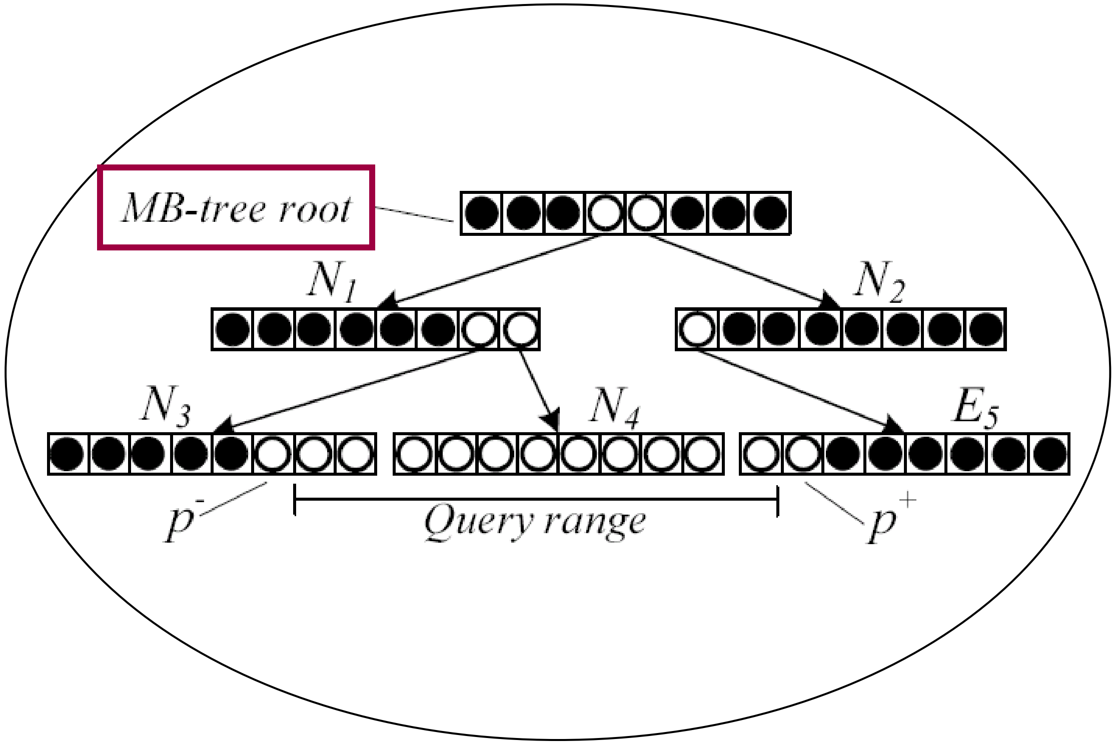
User

Query | Answer + Proof

Query Server

Dynamic Data + Authentication Structure

Data Aggregator (Owner)

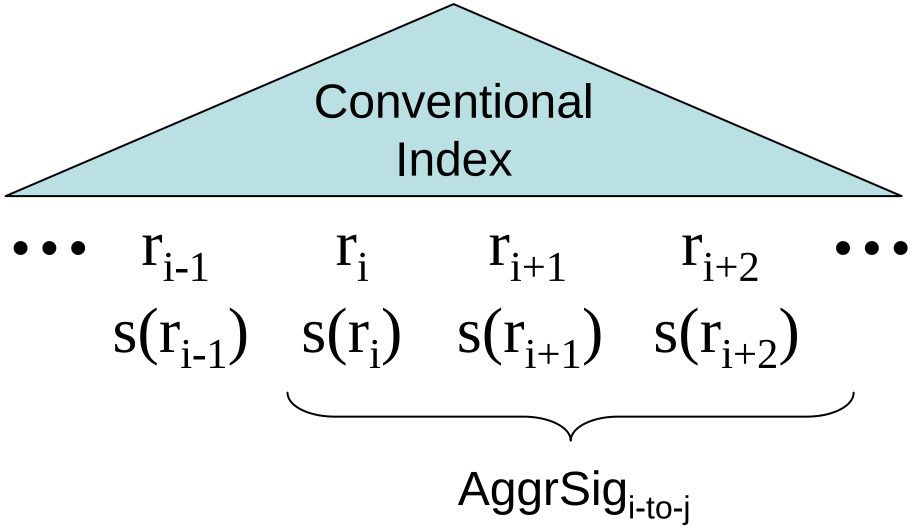


- Queries S-lock the root digest
- Updates X-lock the root digest

⇒ *Locking bottleneck!*

⇒ *Log N update I/Os*

Signature Aggregation Approach

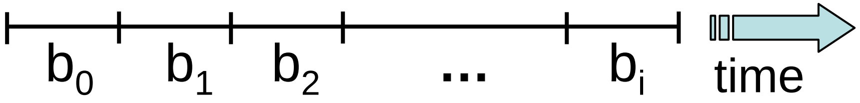


- s(r) = signature of record r
- Suppose answer = $\{r_i, \ldots, r_j\}$
- $AggrSig_{i\text{-to-}j}$ = dynamically computed aggregate on $s(r_i), \ldots, s(r_j)$
- Records can be updated *concurrently*
- Caveat: Signature aggregation operations are much more computationally intensive than hashing function

Challenges with Signature Aggregation

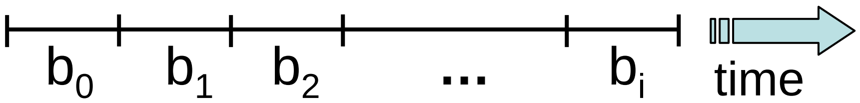
1. How to detect old records and signatures?
   - Not practical to recertify all the records frequently
   - How to invalidate outdated signatures?
2. How to authenticate ad-hoc joins?
3. How to mitigate the much higher computation costs of signature aggregation?

Freshness Protocol



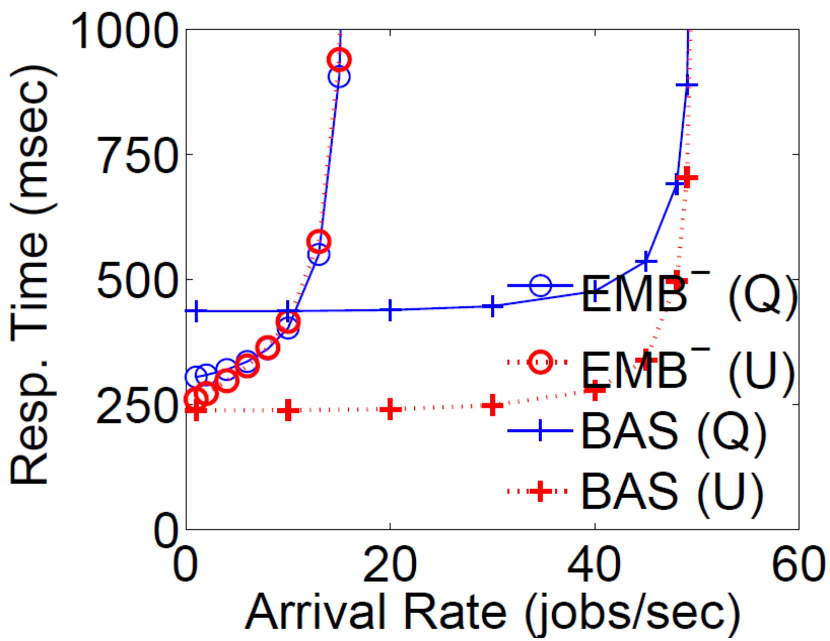
- Data Aggregator releases new record values and signatures to query server and user *immediately*
- Data Aggregator issues a certified bitmap b_i after each time period *i*
- b_i = 0100…110… means that:
  - No change to record 0 in period *i*
  - Record 1 was recertified in period *i*
- Bitmaps are sparse
  - After compression, size is 2 to 3 times the number of 1 bits
  - Proportional to update rate, independent of database size

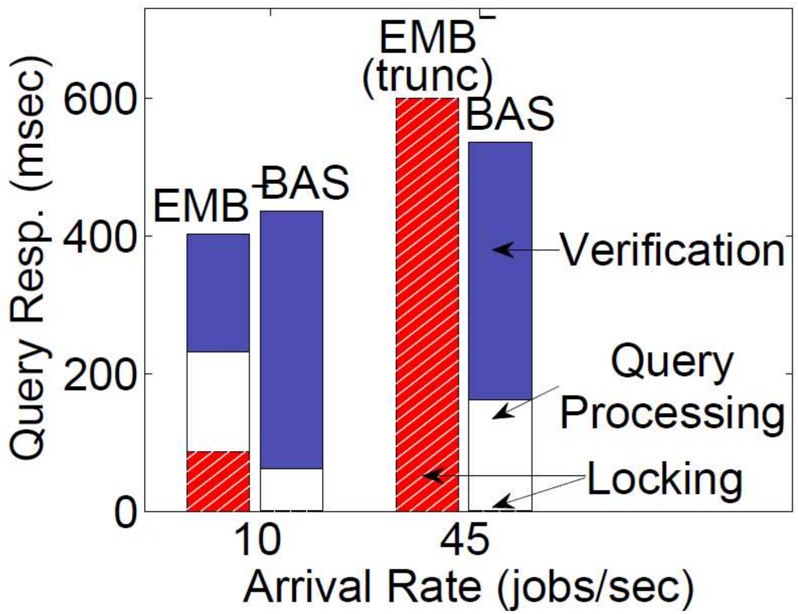
Freshness Check



- Suppose every period lasts ρ seconds, current period is *k*
- A record *j* signed in period *i* is:
  - Current, if $i < k$ and bit *j* is 0 in $b_{i+1}, b_{i+2}, \ldots, b_k$
  - Out of date by at most ρ seconds, if $i = k$
- Details in the paper ...
  - Multiple updates to the same record in a period
  - Background signature renewal to limit the number of bitmaps to be checked
  - Methods for transmitting bitmaps to users, to reduce delays

Experiment Results



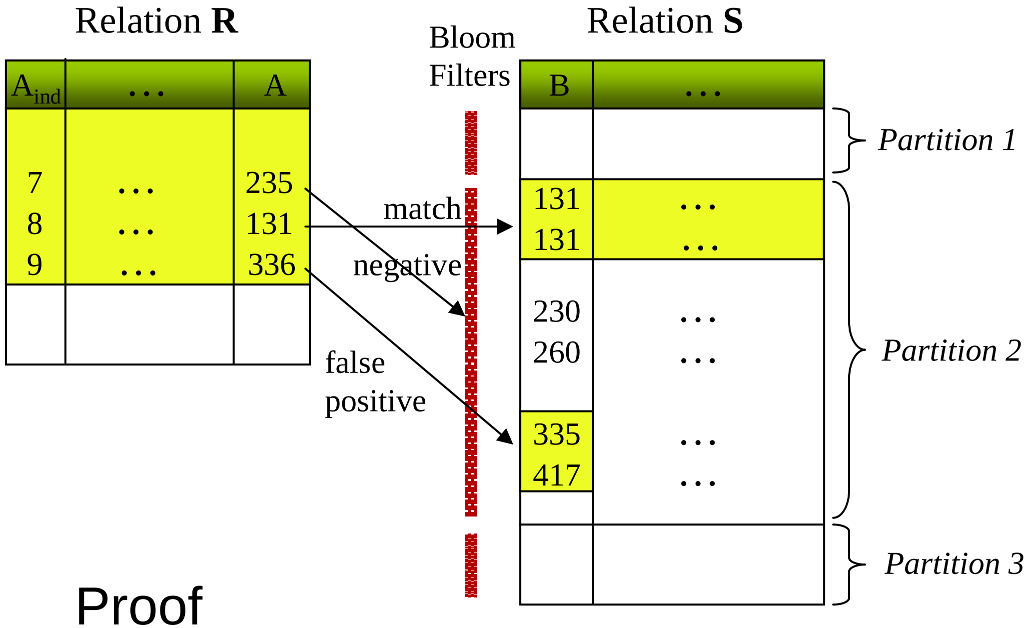


- Database contains 1 million randomly generated records
- Query/update selectivity = 1000 records
- 9 queries to 1 update

Challenges with Signature Aggregation

1. How to detect old records and signatures?
2. How to authenticate ad-hoc join $\mathbf{R} \bowtie_{\mathbf{R}.A=\mathbf{S}.B} \mathbf{S}$?
   - Prove R
   - For record $r \in$ **R** such that $\exists s \in$ **S** with $r.A = s.B$, prove $\sigma_{B=r.A}(\mathbf{S})$
   - How to prove that an *r* record has no match in **S**?
   - Return consecutive $s_1, s_2 \in$ **S** such that $s_1.B < r.A < s_2.B$
   - *Expensive!!*
3. How to mitigate the much higher computation costs of signature aggregation?

Authenticated Ad-Hoc Join $\mathbf{R} \bowtie_{\mathbf{R}.A=\mathbf{S}.B} \mathbf{S}$



- Partition **S** horizontally
- Build a certified Bloom filter $\mathcal{BF}$ on $s.B$ per **S** partition
- $\mathcal{BF}(b)$ = false $\Rightarrow$ b is not in **S**.B (no false negative)
- $\mathcal{BF}(b)$ = true $\Rightarrow$ b is very likely to be in **S**.B (low false positive)

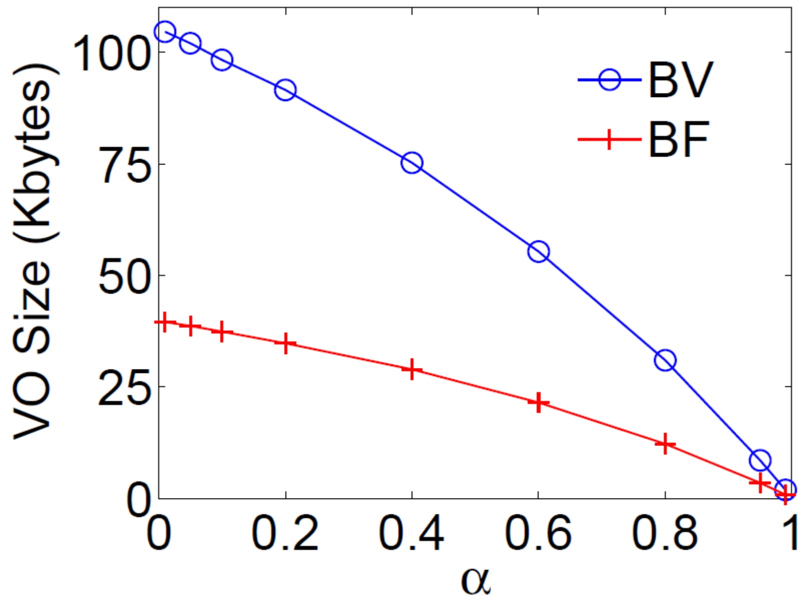
Proof

- Return Bloom filter $\mathcal{BF}$ and partition boundaries if $\mathcal{BF}(r.A)$ = false for some $r \in$ **R**
- Return consecutive $s_1, s_2 \in$ **S** for $r \in$ **R** that has no match in **S**, but $\mathcal{BF}(r.A)$ = true

Details in the paper …

- **S** partition size: proof size versus Bloom filter update cost
- Bloom filter size

Experiment Results

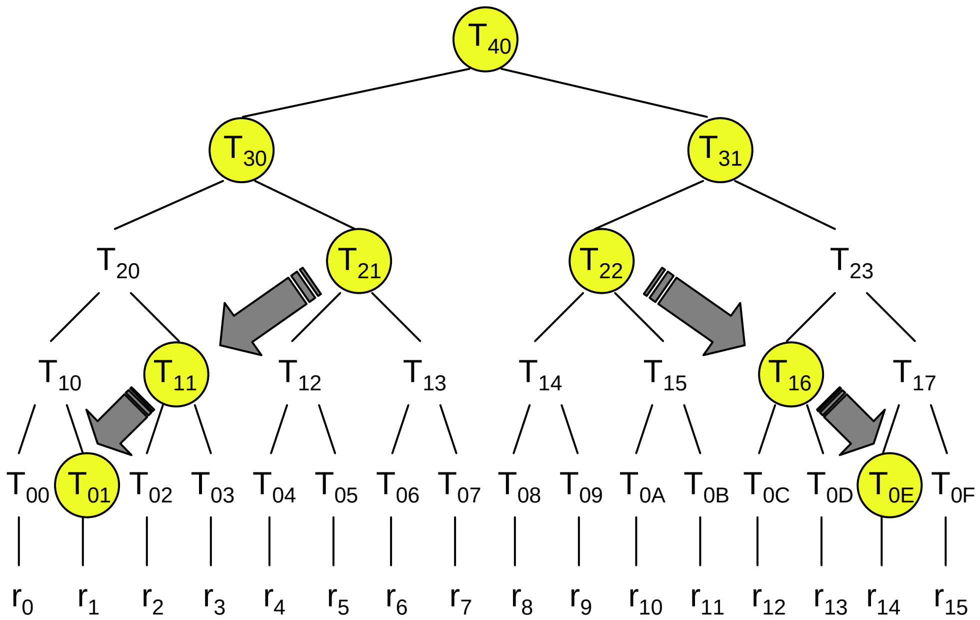


- α = ratio of **R** records with matching **S** records
- BV = always return Boundary Values to prove unmatched **R** records
- BF = use Bloom filters to prove unmatched **R** records

Challenges with Signature Aggregation

1. How to detect old records and signatures?
2. How to authenticate ad-hoc joins?
3. How to mitigate the much higher computation costs of signature aggregation?
    - Aggregating 1000 signatures takes 9 ms (compared to less than 3 μs per hash operation)
    - The Query Server is a shared resource
    - To reduce the number of signature aggregations, can we cache certain “high-utility” aggregates?

Signature Caching



- Imagine a hierarchy of aggregate signatures
- Low-level aggregates are more likely to be reused
- High-level aggregates give more savings when used
- Left-half is symmetrical with right-half

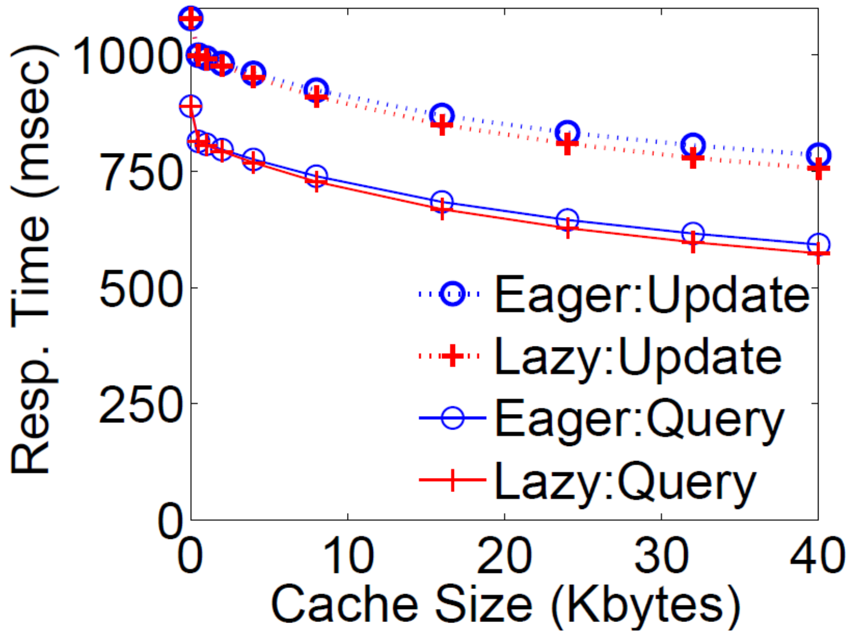
Observations

- Within any level, the 2nd node from the left/right is applicable to the widest range of query cardinalities
- Highest-utility aggregates: 2nd node from level 3 downloads

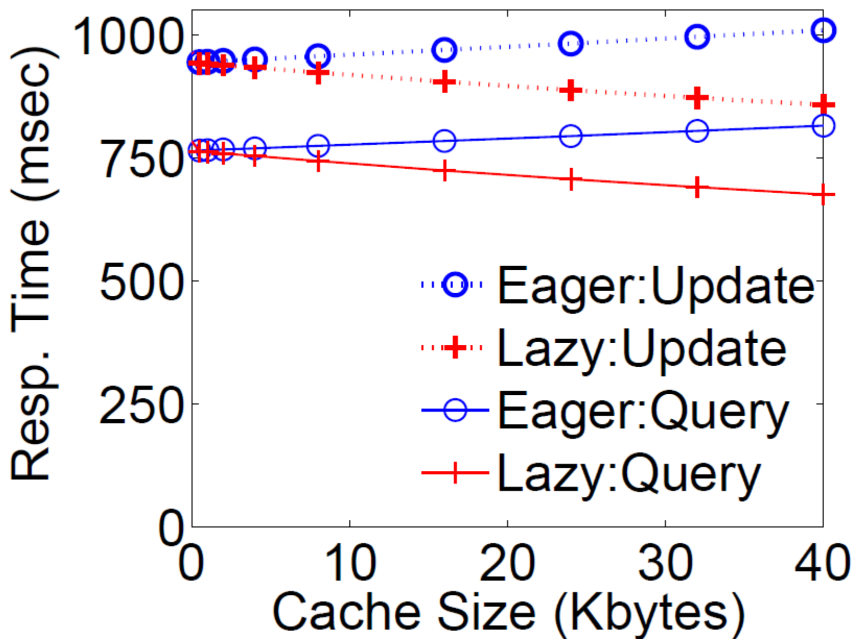
Details in the paper …

- Derivation
- Eager versus Lazy refresh when the underlying signatures change

Experiment Results



(a) 1 update to 9 queries



(b) 4 updates to 6 queries

- Database contains 1 million randomly generated records
- Query selectivity = 1000 records
- Arrival rate = 50 jobs/second

Conclusion

- For outsourced dynamic databases, the criteria for query answer correctness include authenticity, completeness and *freshness*
- The scalability of Merkle hash tree approaches is limited by lock contention
- We introduced a scalable verification protocol, based on signature aggregation approach, that supports freshness guarantee
- We proposed an authentication mechanism for ad-hoc joins
- We demonstrated that caching a small number of aggregate signatures can significantly help the query server