POPE: Partial Order Preserving Encoding

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Problem: Encrypting a Database Index

Cloud databases are popular for many reasons:

- Low cost
- High availability
- High performance
- ...

But these systems are regularly compromised by attackers.
(Consider just voter databases in the last year!)

Challenge: Securing data without compromising performance (too much)

Tradeoffs and Choices

1. **Features**
   (Query support, multi/single user)
2. **Performance**
   (Server time/memory, client time/memory, transfer size, rounds)
3. **Privacy**
   (What might be leaked? What kind of adversary?)

Our Target Features

This work focuses on a common big data scenario:

- Many insertions (should be as fast as possible)
- Fewer lookups or range queries

Data: Key/value store, i.e. all queries on a single column.

Example Dataset

4 million employees, with lookups by salary.
(California public employees database)

This talk

Focusing on many insertions and fewer range queries:

1. Existing approaches, performance/privacy tradeoffs
2. Our construction: POPE
   Provides a new compromise between performance and privacy
3. Evaluation and experiments

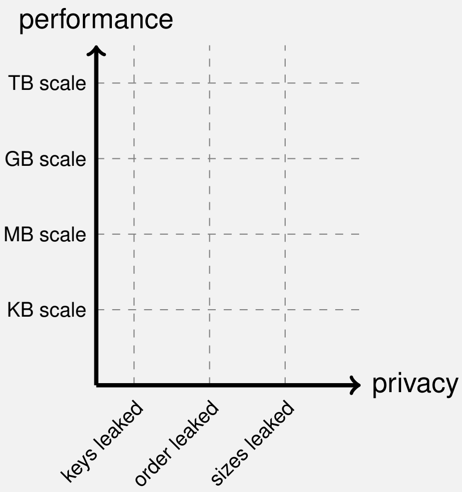
Context of POPE

Our target: Many insertions, few range queries

Current options:

- No encryption
- Traditional OPE
- PPE, ORE, or Interactive OPE
- ORAMs
- Encrypt the entire database

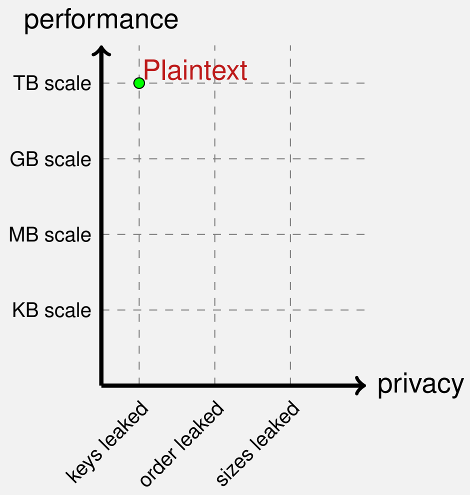
POPE will provide a new compromise in this space



Storing keys in plaintext

Trivial solution:
Store keys in plaintext, encrypt payloads only

Possible with any existing cloud database solution.



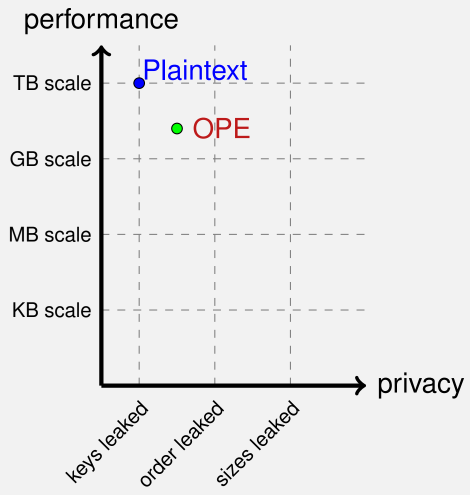
Order-Preserving Encryption (OPE)

Idea:
Can compare keys by comparing ciphertexts.

These schemes are used in industry today!

Hot topic:

- Agrawal et. al.'04
- Baldyreva et. al., '09, '11
- Mavroforakis et. al., '15
- Lewi & Wu '16 (ORE)



Order-Preserving Encryption (OPE)

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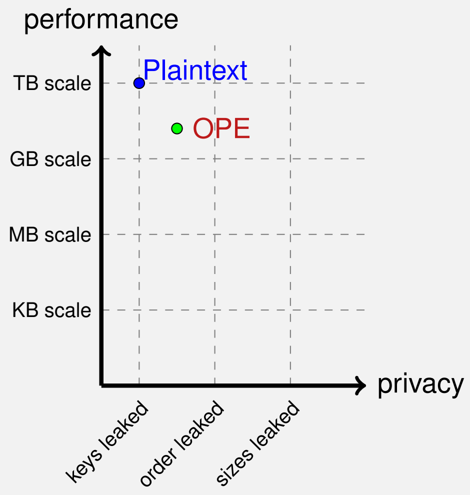
Hot topic for attacks:

- Baldyreva et. al.'11
- Naveed et. al.'15
- Durak et. al.'16
- Grubbs et. al.'16



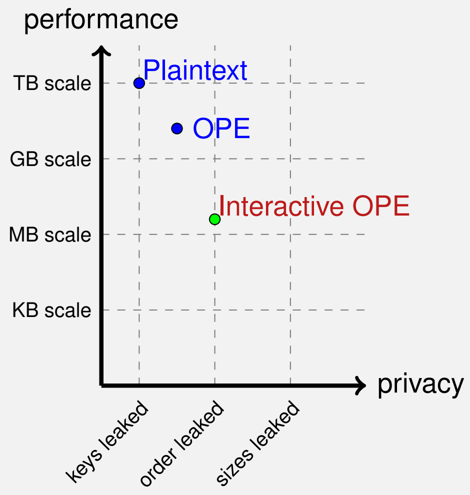
Interactive OPE

Idea:
Use an interactive protocol to compare ciphertexts

Achieves ideal security leaking only the order

- Popa et. al.'13
- Kerschbaum et. al., '14
- Kerschbaum '15
- Boelter '16

(Ideal ORE of Boneh et. al.'15 fits most closely here.)

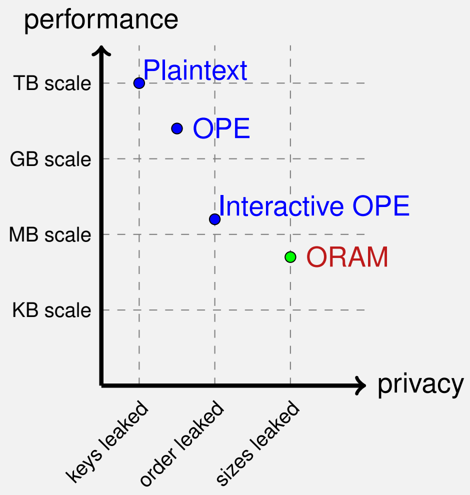


Oblivious RAM (ORAM)

Idea:
Store data structure in an ORAM to hide access patterns

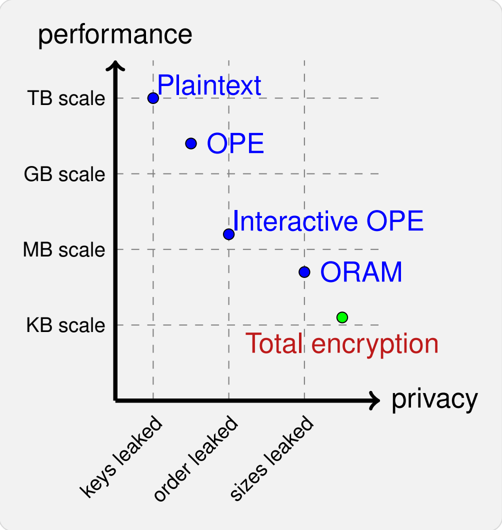
- Goldreich & Ostrovsky '96
- Stefanov et. al. '13
- Wang et. al. '14
- Devadas et. al. '15
- R., Aviv, Choi '16

. . . and many more!



Encrypt the whole thing

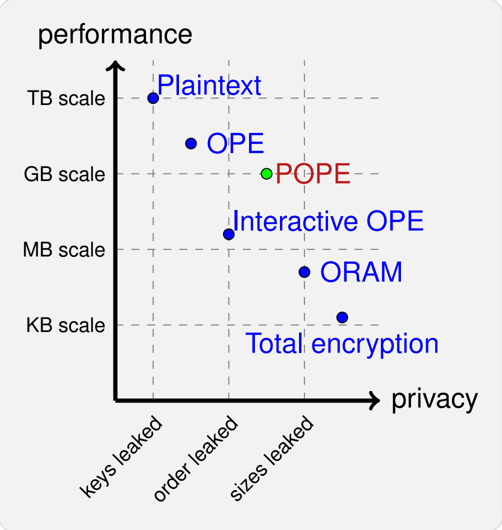
Trivial solution:
Download and re-encrypt the whole database on each access



This talk: *Partial* Order Preserving Encoding

Our idea:
Only perform comparisons necessary to execute the queries.

Improves performance *and* security compared to interative OPE



POPE Data Structure

Main Idea

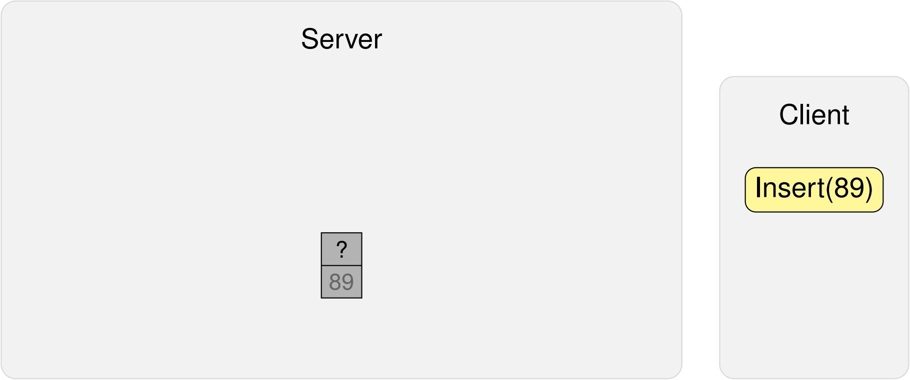
- Server stores a *partially ordered* B-tree
- Every node contains an unordered buffer of key/value pairs
- Non-leaf nodes also have a small ordered list of ciphertexts
- Encryption uses any (randomized) symmetric cipher
- Client performs comparisons at query-time

Influences:

- Buffer trees (Arge '03)
- Mutable OPE (Popa, Li, Zeldovich '13)

Initial insertions

Inserted ciphertexts are appended (unordered) to the root node.



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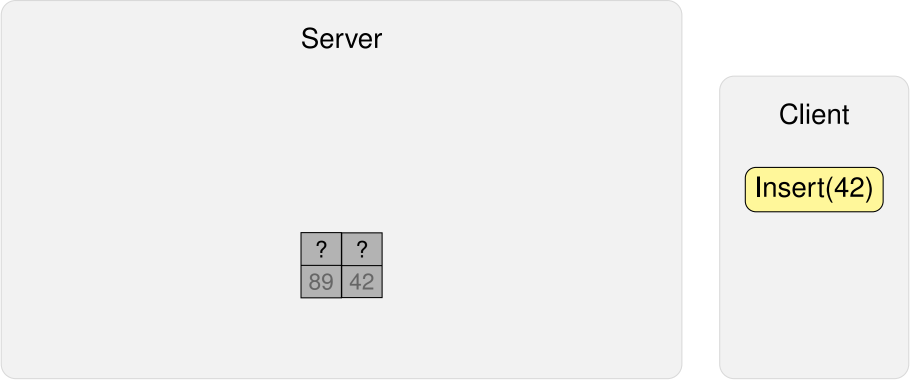
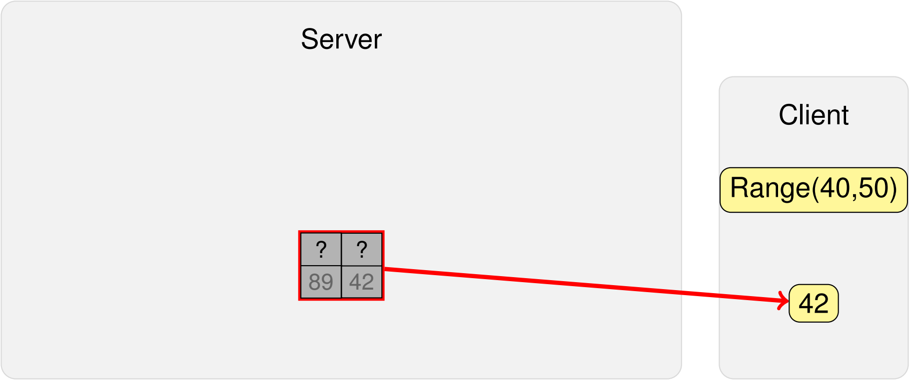


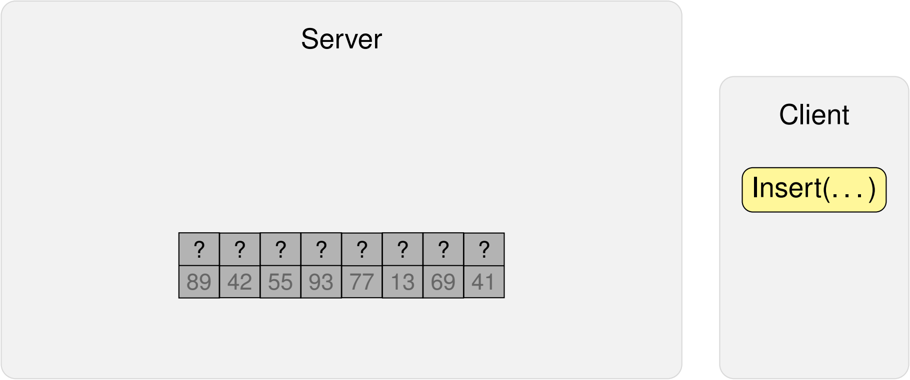
Range search Base case

For a small leaf node, send the entire node to the client.



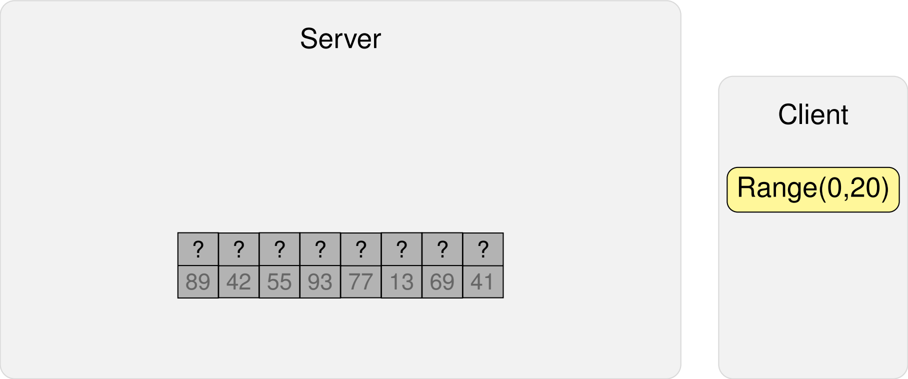
More insertions

Further insertions are appended to the root.



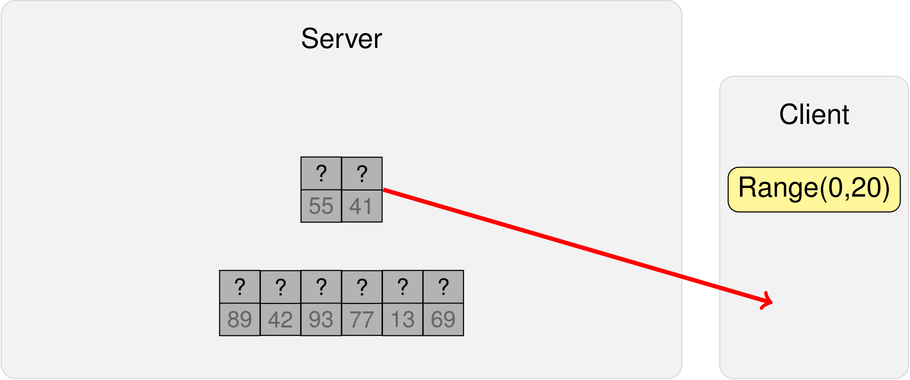
Splitting leaf nodes

Searching a large leaf node requires *splitting*.



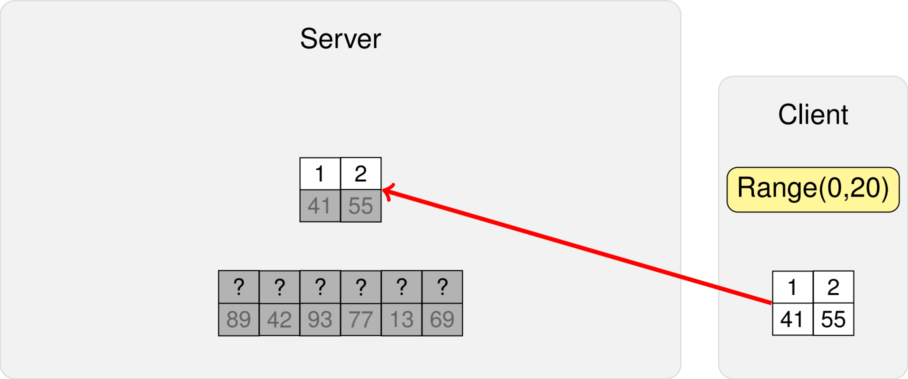
Splitting leaf nodes

1. Server promotes m random items and sends to client.



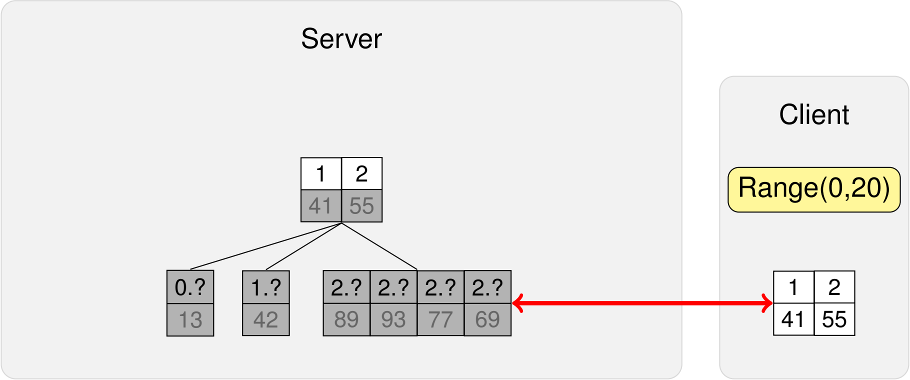
Splitting leaf nodes

2. Client sorts, stores, and remembers the m items.



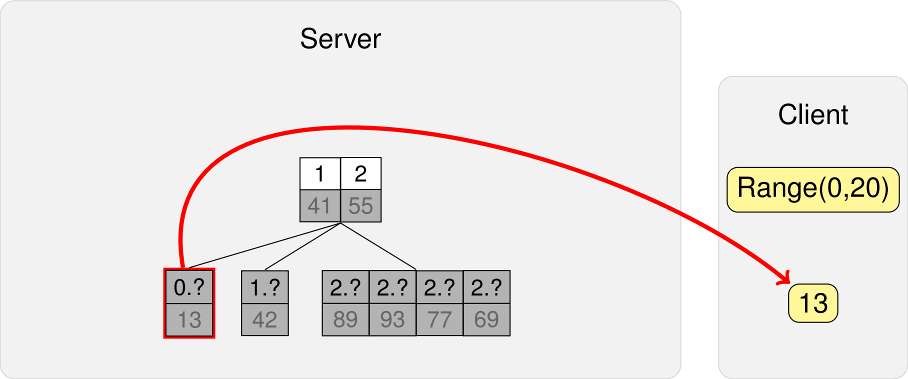
Splitting leaf nodes

3. Client partitions remaining items.



Splitting leaf nodes

4. Finally, the range query results are returned.



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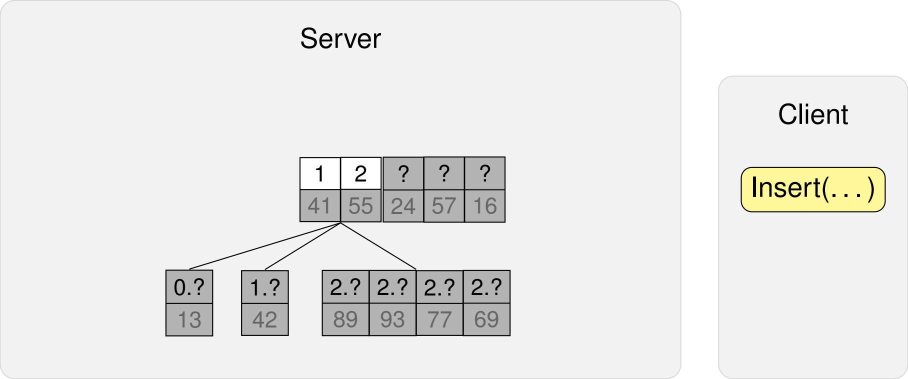
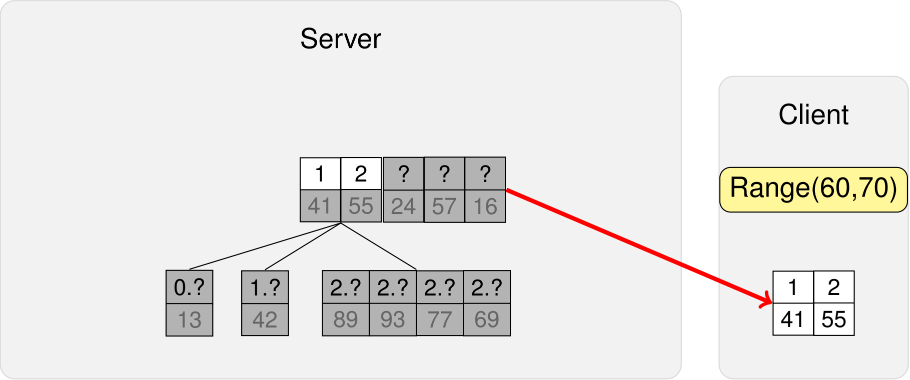


Range query

Queries start by partitioning the root buffer to child nodes.



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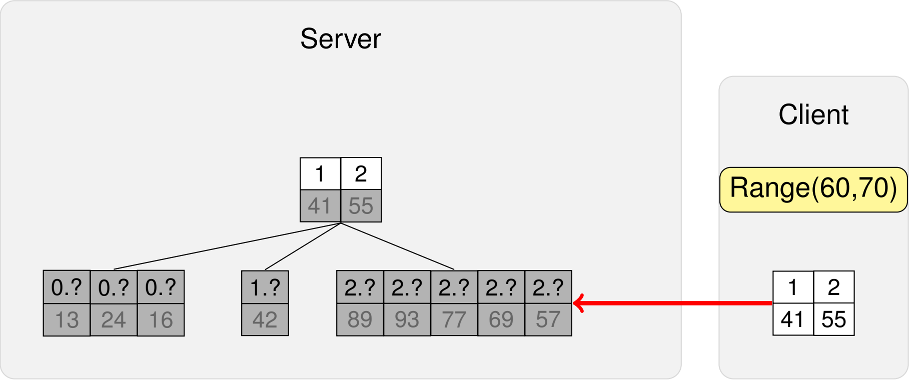
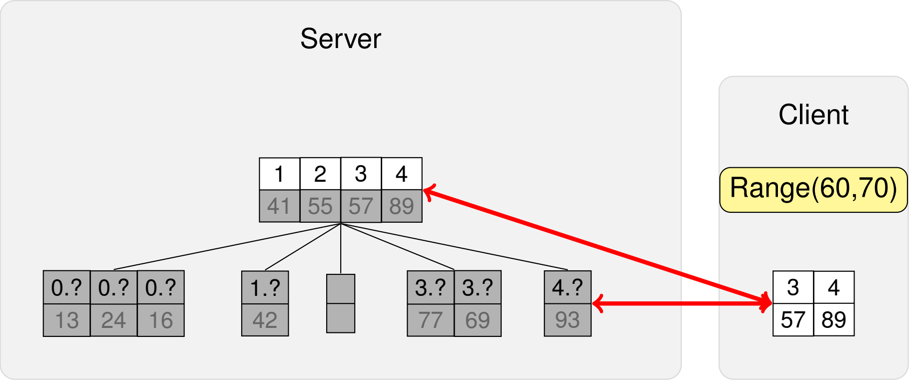


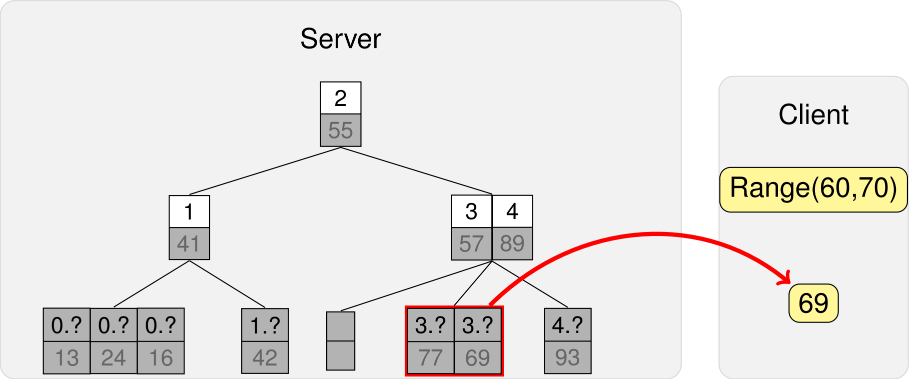
Range query

This may result in further leaf node splits.



Range query

The sorted parts of nodes are not allowed to get too large.



Performance

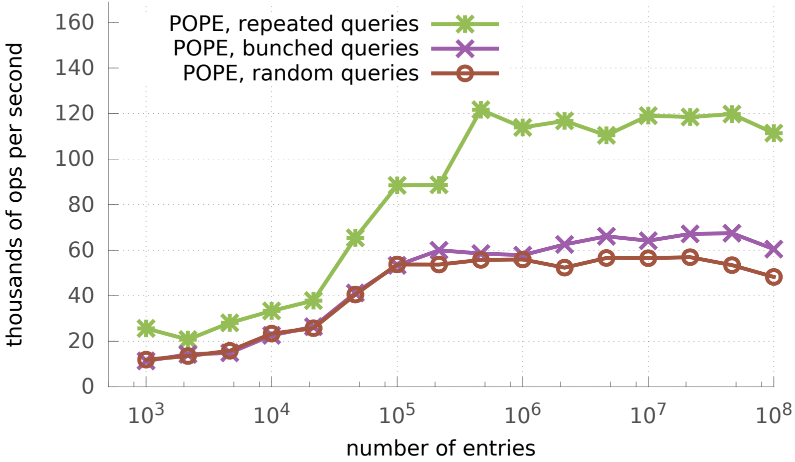
While *some* queries may be costly due to interactive partitioning, the *average* cost per operation is optimal:

Amortized Analysis

The average cost per operation is $O(1)$, and
the worst-case round complexity per operation is $O(1)$, assuming:

- n insertions
- Reasonable client-side temporary storage ($L \in \Omega(n^{O(1)})$)
- Not too many range queries ($m \leq \frac{n}{L}$)

Experimental Performance



Note: Number of queries was $\sqrt{n}$ in all cases.

POPE Security

Server cannot learn more than the order of the keys.
(IND-OCPA notion of Boldyreva et. al. '11, achieved by Popa et. al. '13)

Tie-breaking randomness hides key frequencies also.
(IND-FAOCPA of Kerschbaum '15)

Only a partial order is leaked.
Under previous assumptions of n insertions, m queries and client storage L, the relative order between at least

$$\Omega\left(\frac{n^2}{mL} - n\right)$$

pairs of elements is not revealed.

Thanks!

The Paper

Daniel S. Roche, Daniel Apon, Seung Geol Choi,
and Arkady Yerukhimovich
"POPE: Partial Order Preserving Encoding"
`https://arxiv.org/abs/1610.04025`

Code: `https://github.com/dsroche/pope`

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