Parakeet: Practical Key Transparency for End-to-End Encrypted Messaging

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joint work with
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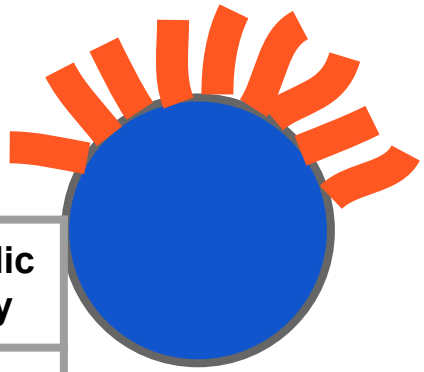
End-to-End Encrypted Messaging

Encrypted Messaging Service + **Identity Provider**

Alice

`1800-ali-ce`

Username	Public Key
`1800-ali-ce`	PK_{alice}
`100-bob-ph`	PK_{bob}



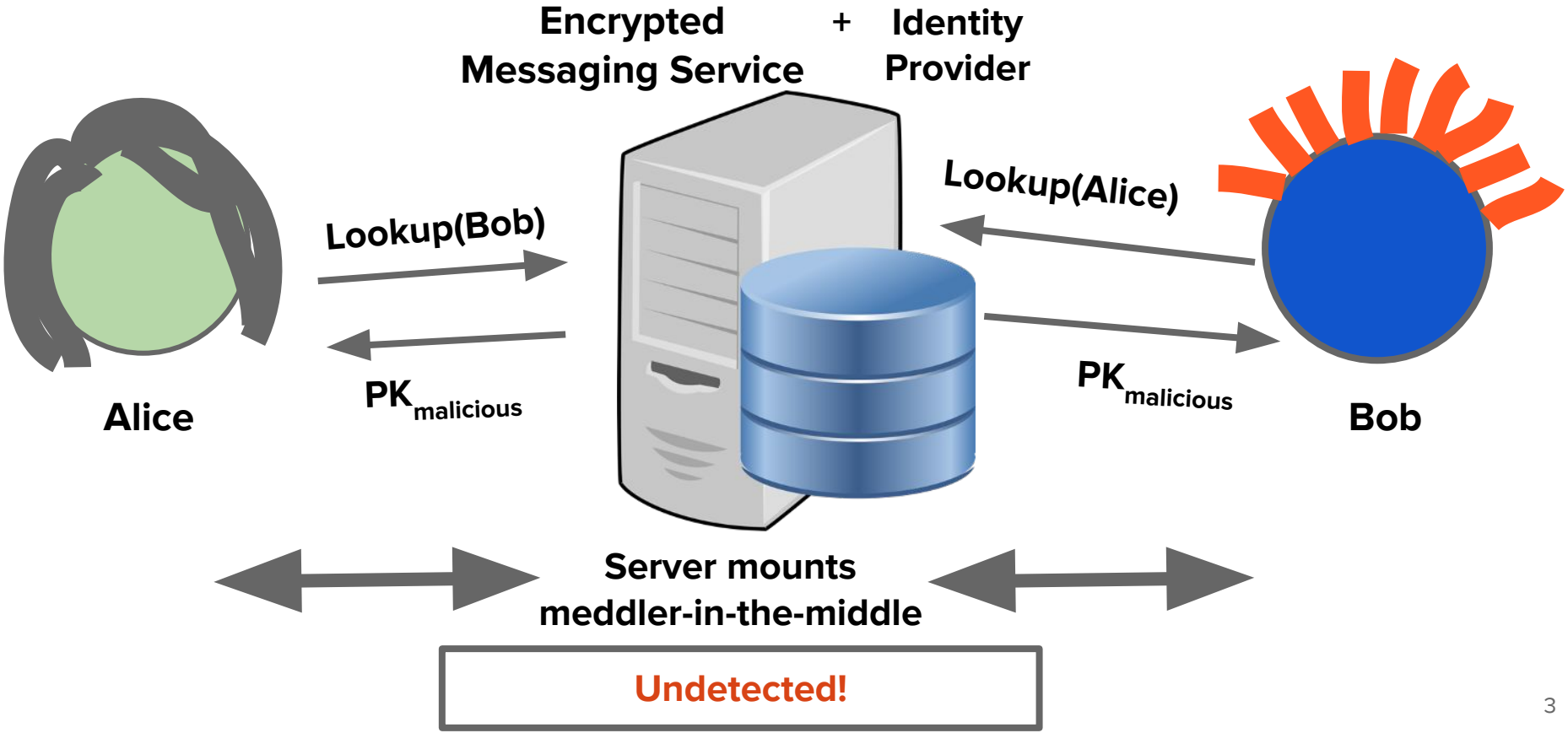
Bob

`100-bob-ph`

Want to send encrypted messages

Need Each Other's Public Keys

End-to-End Encrypted Messaging

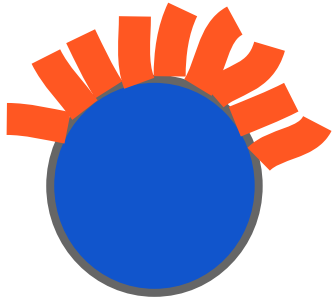


Transparent (Privacy-Preserving) Dictionaries

Identity provider holds a dictionary with username-PK pairs, such that

- **New Users:** New users may join.
- **Changing state:** Users "own" their usernames and can update PKs.
- **Privacy:** Users want the server to restrict queries to their usernames.

Identity provider could cheat: Same username queried at the same time ➔ diverging value.



Uname	PK
Alice	PK_{alice}
Bob	PK_{bob}

More General

- Privacy-preserving centralized financial ledger:
  - Central server trusted for privacy + ordering. ✅
  - Not trusted for serving correct state, e.g. FTX. ✅
- Certificate transparency, tamper evident logging.
  - No **privacy** requirement, ❌
  - Larger **computation at clients**. ❌
  - Usually only for “logging” not mapping. ❌

Label	Value
Alice	$\text{WalletAddr}_{\text{alice}}$
Bob	$\text{WalletAddr}_{\text{bob}}$

FTX Server

Key Transparency Security Guarantee

- Threat model:
  - IdP holds dictionary,
  - May “cheat”: show diverging views to different parties.
- Ideal: want to *prevent* the IdP from cheating at all.
- Assumptions on clients:
  - Need them to store secrets, etc.
- Security = **non-equivocation**:
  - Cannot show different keys to different clients w/o getting caught.
  - At any given time:
    - Alice thinks her key is $\mathbf{PK}_{\mathbf{Alice}}$ ⇒ the server cannot get away with telling Bob her key is $\mathbf{PK}_{\mathbf{BAD}}$.

Model: Parties

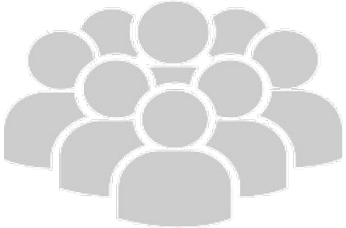
Identity Provider

- Trusted for privacy and authentication.
- **Want to eliminate trust for serving correct public keys.**
- Updates are batched and take effect in discrete time steps called *epochs*.

Users

- May update their public key.
- Lookup each other's public keys if permitted e.g. not blocked.
- Check their own keys' history up till the present epoch.
- **Want no changes to their keys without their finding out.**
- **Their friends should receive matching keys for them.**

Auditors



- Share some computational burden.
- **Check global predicates.**
- Audit(start_epoch, end_epoch): Check that the server's state changes between these epochs are valid. E.g., the server doesn't destroy records.
- Could be users, smart contracts, designated machines, unrelated third-parties, etc.
- **Should not learn data about particular users!**

Key Transparency Components + Desiderata

Components

- Mechanism for server committing to mutating state.
- Mechanism to allow users to monitor their own keys.
- Need some ground truth, i.e. way to share a small commitment.

Also would like to be able to support

- **Billions** of users.
- Users with computationally limited devices.

Model

Identity Provider

Need a way to commit to this:

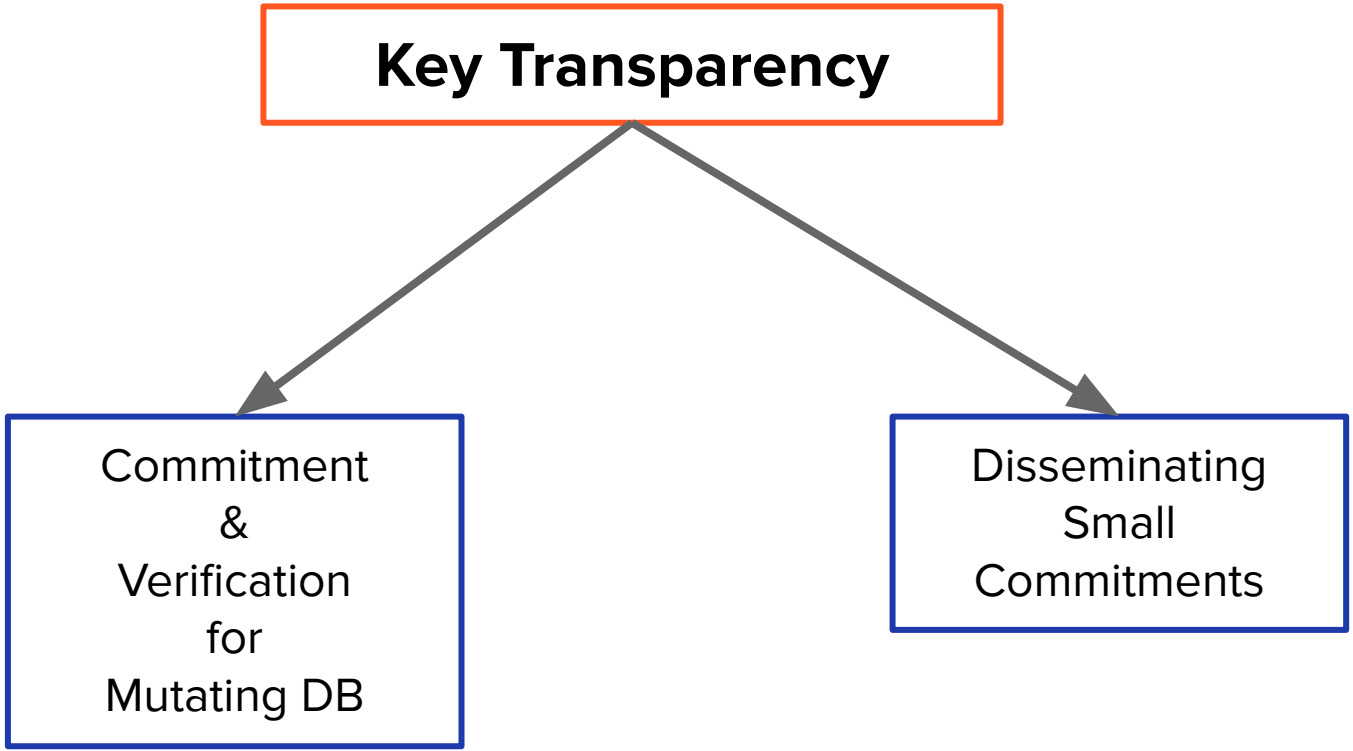
com_{state}

Serving commitments:
Need a way for users to access com_{state}

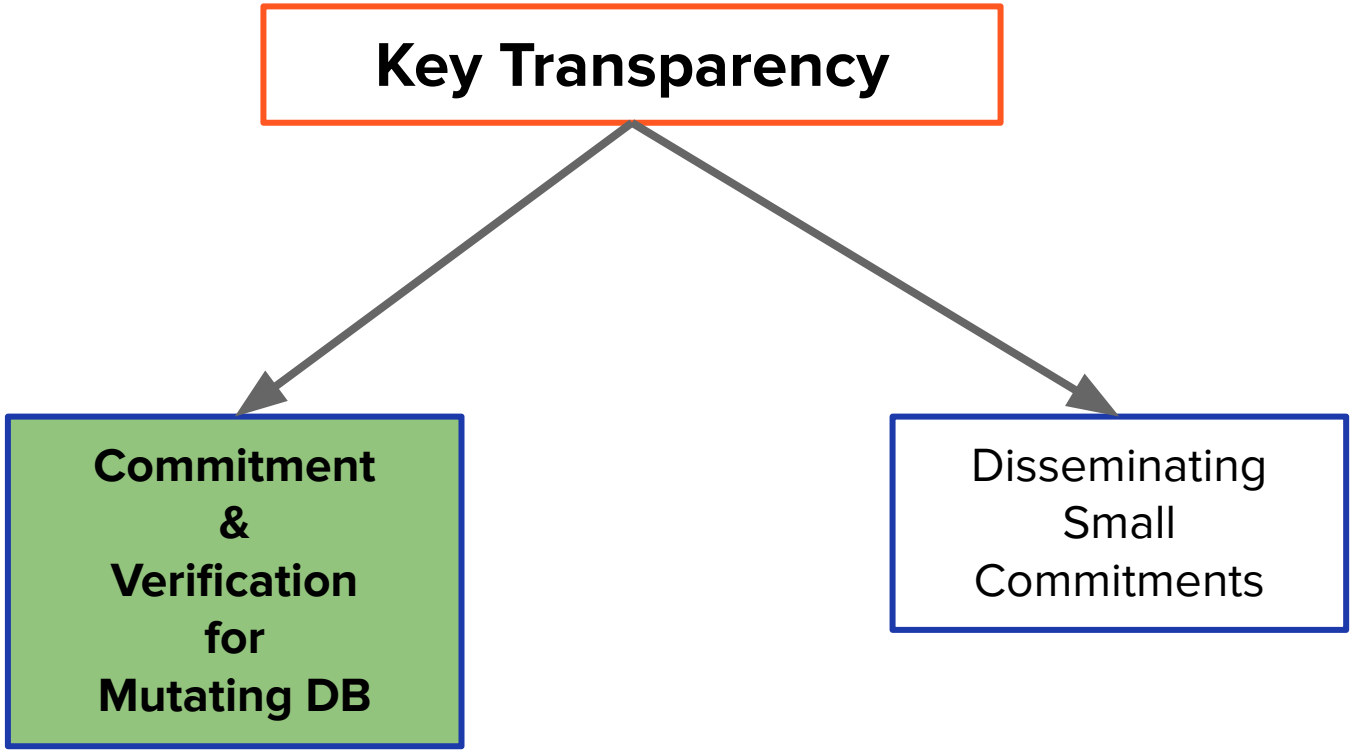
Username	Public Key
User1	PK_{user1}
User2	PK_{user2}
…	…

Identity Provider's State

Problem Breakdown



Committing to Server State



Committing to Server State

Committing to this:

com_{state}

Username	Public Key
User1	PK_{user1}
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…	…

Identity Provider's State

Identity Provider

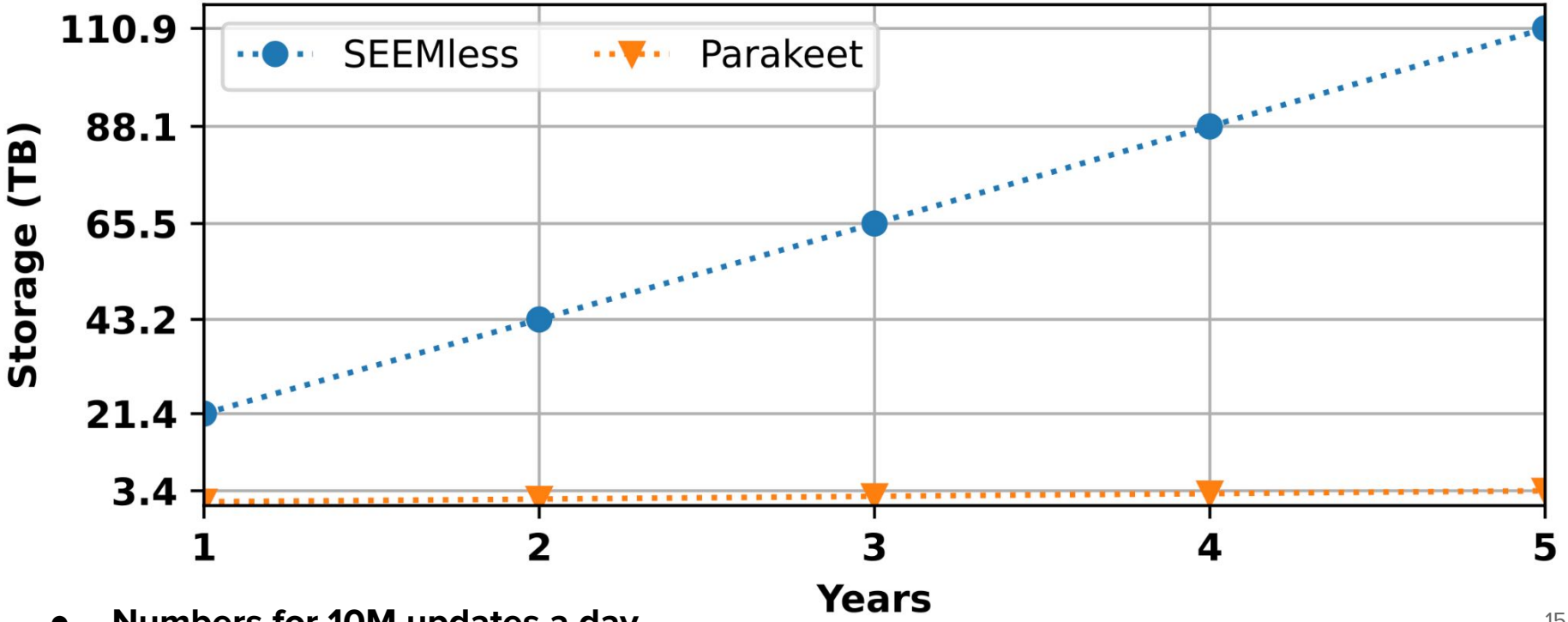
Committing to Server State: Previous Work

- **Committing to state:** Solutions based on Merkle Trees or other kinds of vector commitments.
- **Reducing user load:** Reduce user computation using third-party auditors or SNARKs etc.
- **Users monitoring key history:**
  - **Append-only** authenticated data structures to prevent the server from cheating and then erasing evidence.
    - NO STATE CHANGES EVER DELETED.
  - OR users must do **linear work in server epochs** to monitor their own keys...
  - OR server must generate expensive proofs.

Committing to State: This Work

Problem	Previous Work	Pitfall	Our Work
State machine replication, storage layer separation.	Abstracted away, experiments used single machines.	Entire large data structures cannot be read locally	Flexible storage layer API: modularly plugs in existing DBs.
Data structure for state commitments	Grow to ~100s of TB over years	Storage cost blowup	Replace underlying data structure (oZKS)

Comparing Storage Costs



- Numbers for 10M updates a day

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Users checking own key	• ZKP • Always online • Append-only data structures	• Impractical for server • Impractical for client • Ever growing storage costs	Secure compaction: Find a middle ground between requiring users always online and totally append-only.

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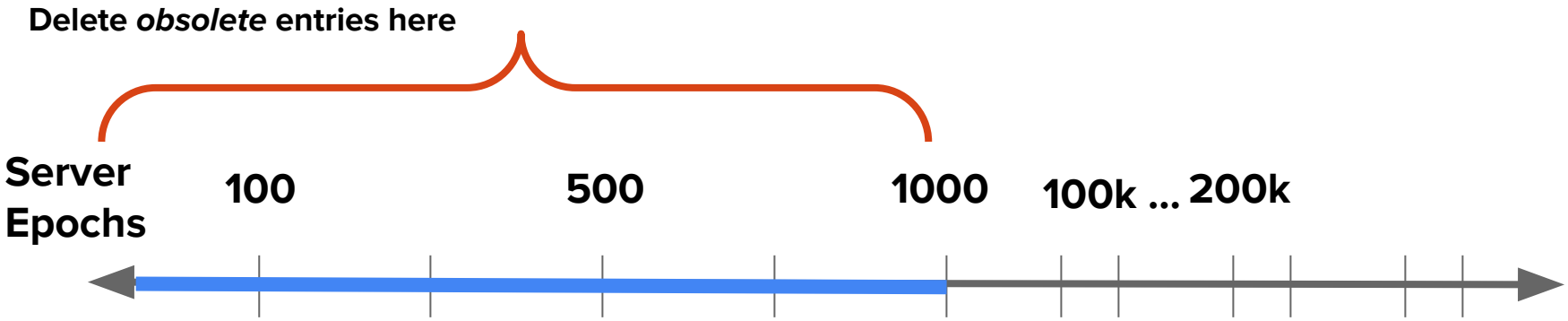
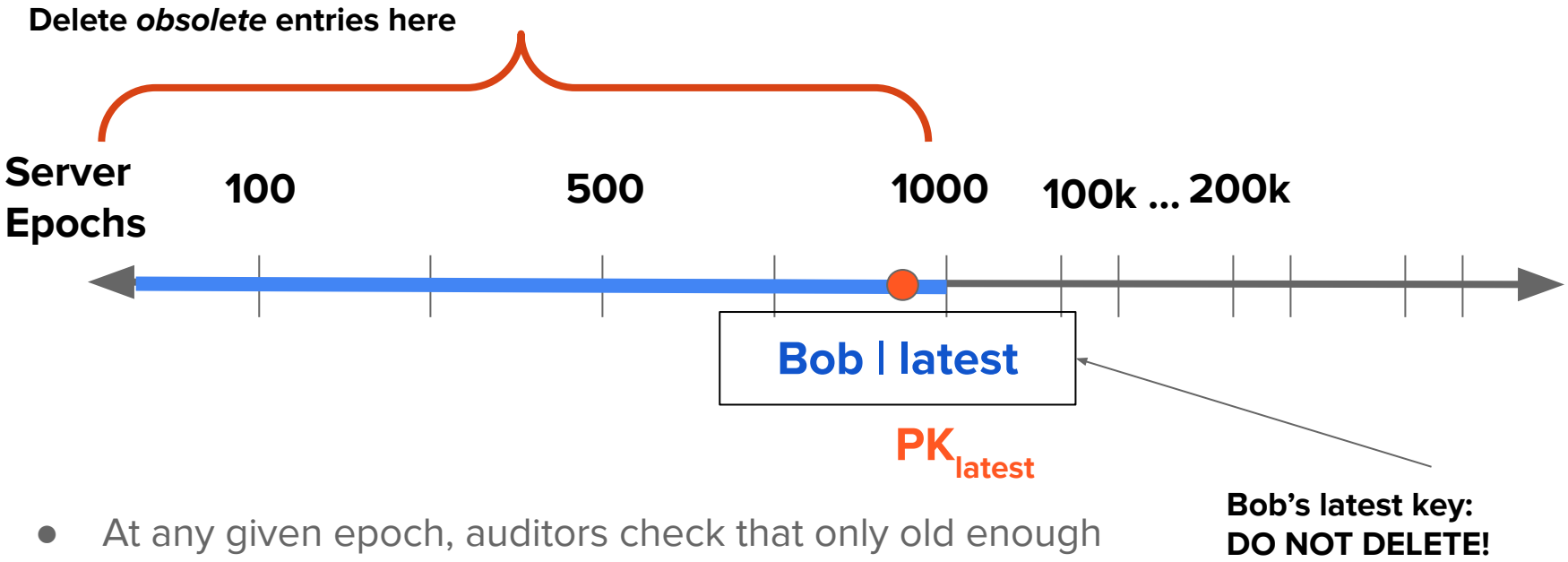
Secure Compaction: Attempt 1



- At any given epoch, auditors check that only old enough entries are deleted.
- **Problem:** Some old data may still be relevant.

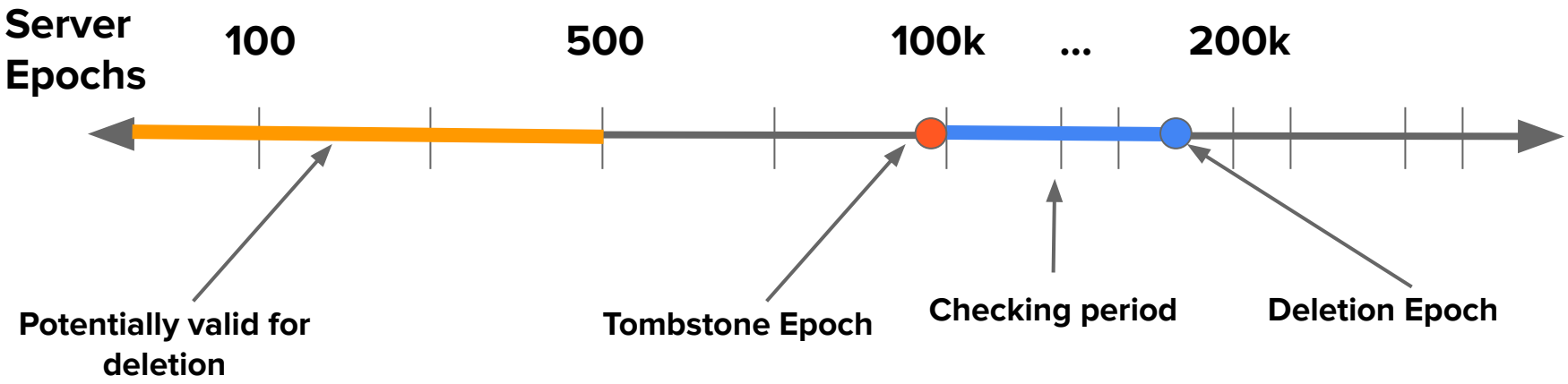
Secure Compaction: Attempt 2



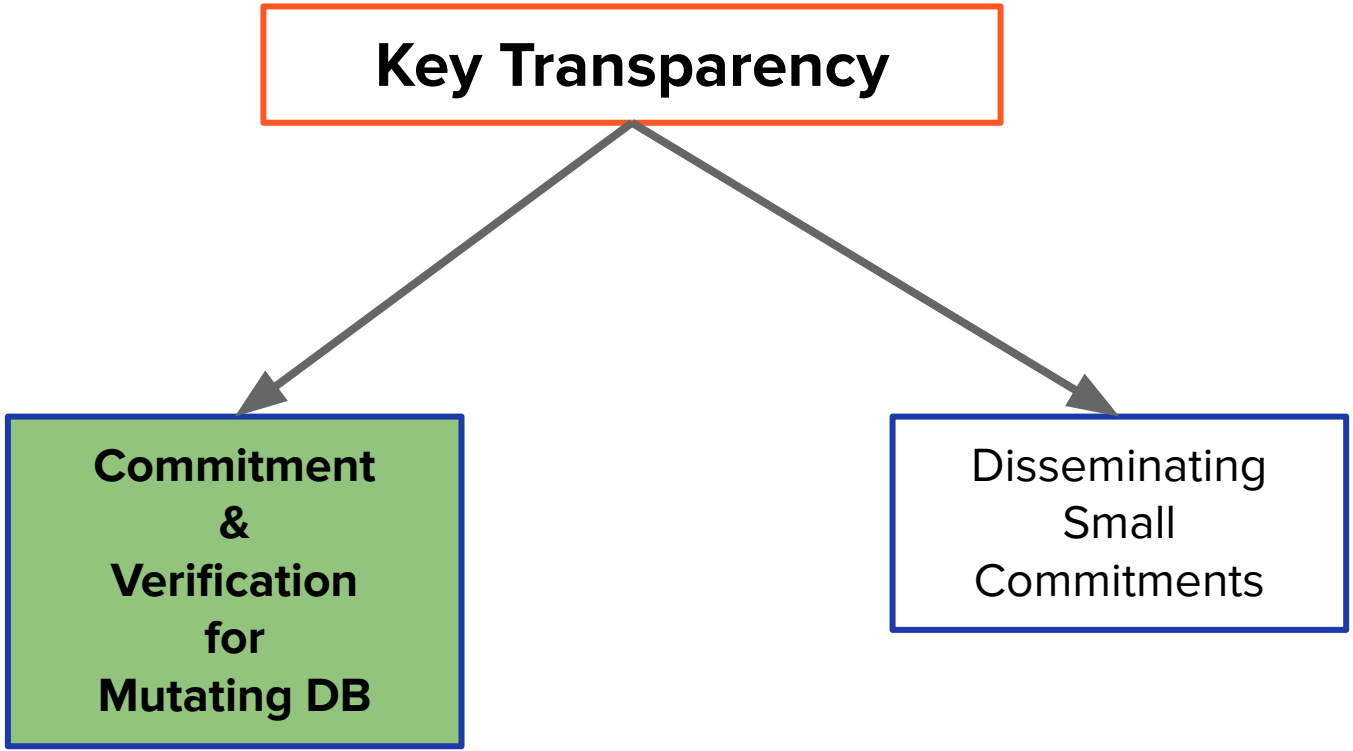
- At any given epoch, auditors check that only old enough entries are deleted.
- Show that for any deleted entry, there exists some update superseding it.
- **Problem:** Leaks metadata for users!

Secure Compaction

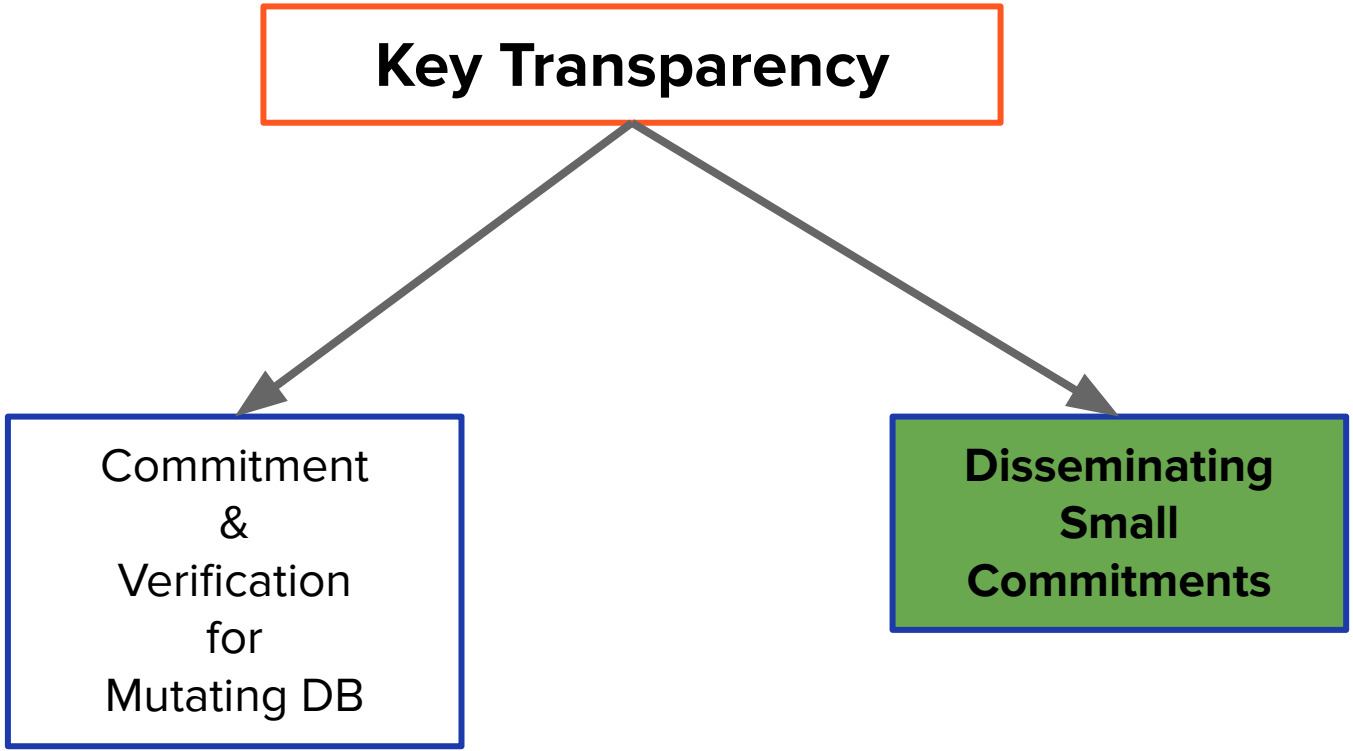
- Involve both individual users and auditors.
- Well-defined (and sparse) epochs for deletion-related ops.
- Provide a grace period or checking period where values are *tombstoned*.
- Auditors check everything tombstoned is old enough.
- Users come online to check that only expired values for them are marked for deletion.
- Garbage collection after grace period is over.



Committing to Server State



Serving Commitments



Serving Commitments

Identity Provider

Need a way to commit to this:

com_{state}

Serving commitments: Need a way for users to access com_{state}

Username	Public Key
User1	PK_{user1}
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…	…

Identity Provider's State

Sharing a small commitment: Gossip?

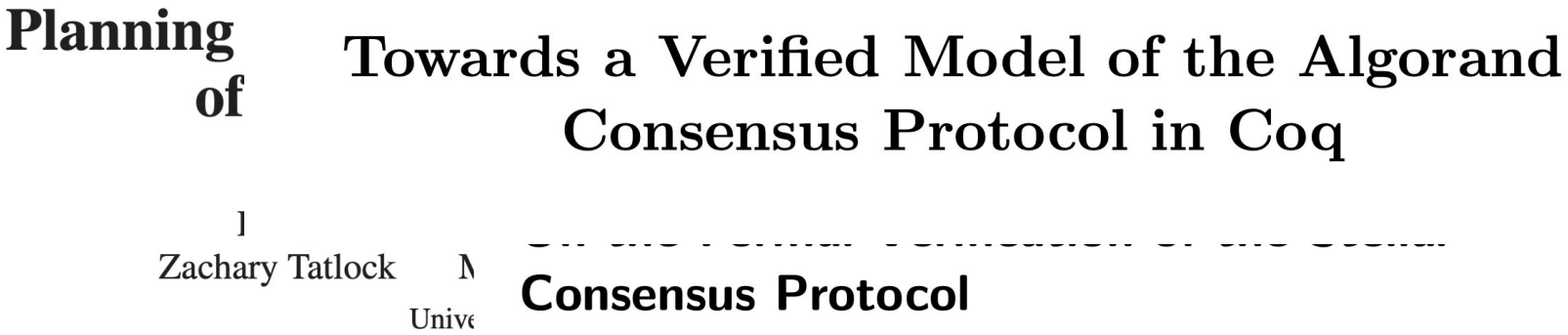
- If users have an out-of-band communication mechanism, they could gossip the commitment they get, i.e. share their views.
- Problem for a global scale system because:
  - Might end up with partitions in the network of users, for example geographically.
  - Users may come online intermittently.
  - Users may not have the bandwidth (or enough battery) to gossip!
  - Dissemination might be too slow.

Sharing a small commitment: Blockchains?

- Could post the commitment in a smart contract or OP_RETURN on bitcoin.
- Must trust the blockchain and its code.
- Even “light” clients could be too heavyweight.
- If billions of users query, could end up flooding the network with queries!

Custom Consensus for Strong Consistency?

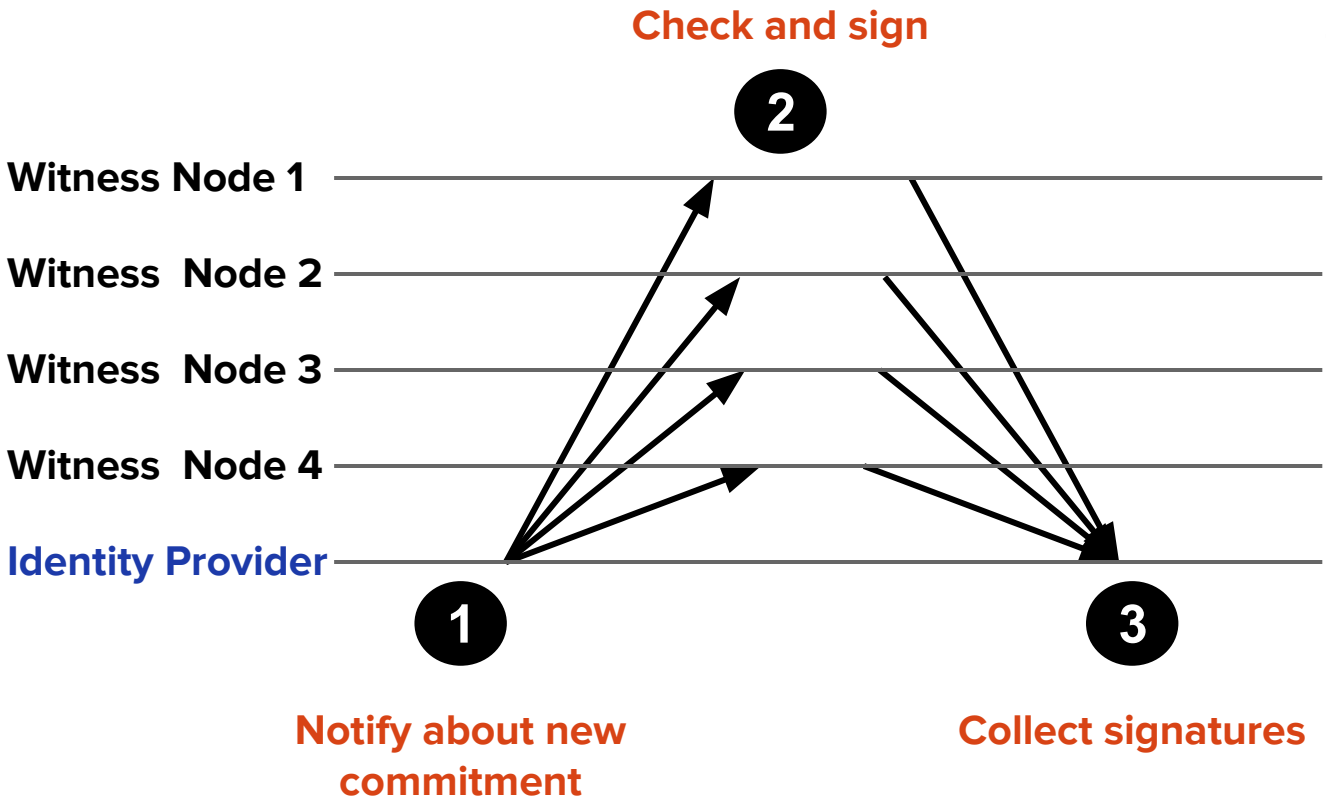
- Blockchain ➔ Consensus.
- Is consensus really needed?
- Consensus pitfalls:
  - N^2 communication cost
  - Delays
  - Complex to implement and analyse



Consensus-less Strong Consistency

- Server is trusted for compiling the updates and finalizing the underlying database.
- Server also has infrastructure for compiling and serving messages from some sort of “independent witnesses”.
- Let’s use **witnesses**!
  - Multiple trusted hardware instances.
  - Industry consortiums.
- Witnesses store the latest commitment and check new commitment is ok.

Consensus-less Strong Consistency



Communication:

- IdP ↔ Witnesses
- IdP ↔ Users
- Witness ↚↛ Witness
- Users ↚↛ Witnesses
- Clients accept if a threshold number of witnesses sign.

Consensus-less Strong Consistency

- Consistency, validity and termination are guaranteed similar to BFT consensus protocols.
- No liveness but much faster!
- Can be used in addition to other mechanisms.
- Simple protocol, easier to implement and fewer bugs.
- Uses existing server infrastructure.
- Users get certified commitments together with proofs and query responses.

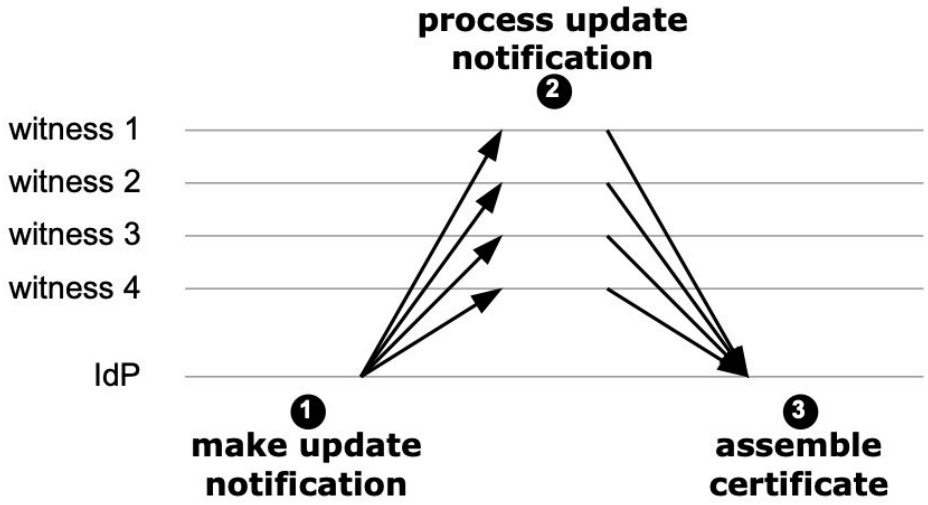
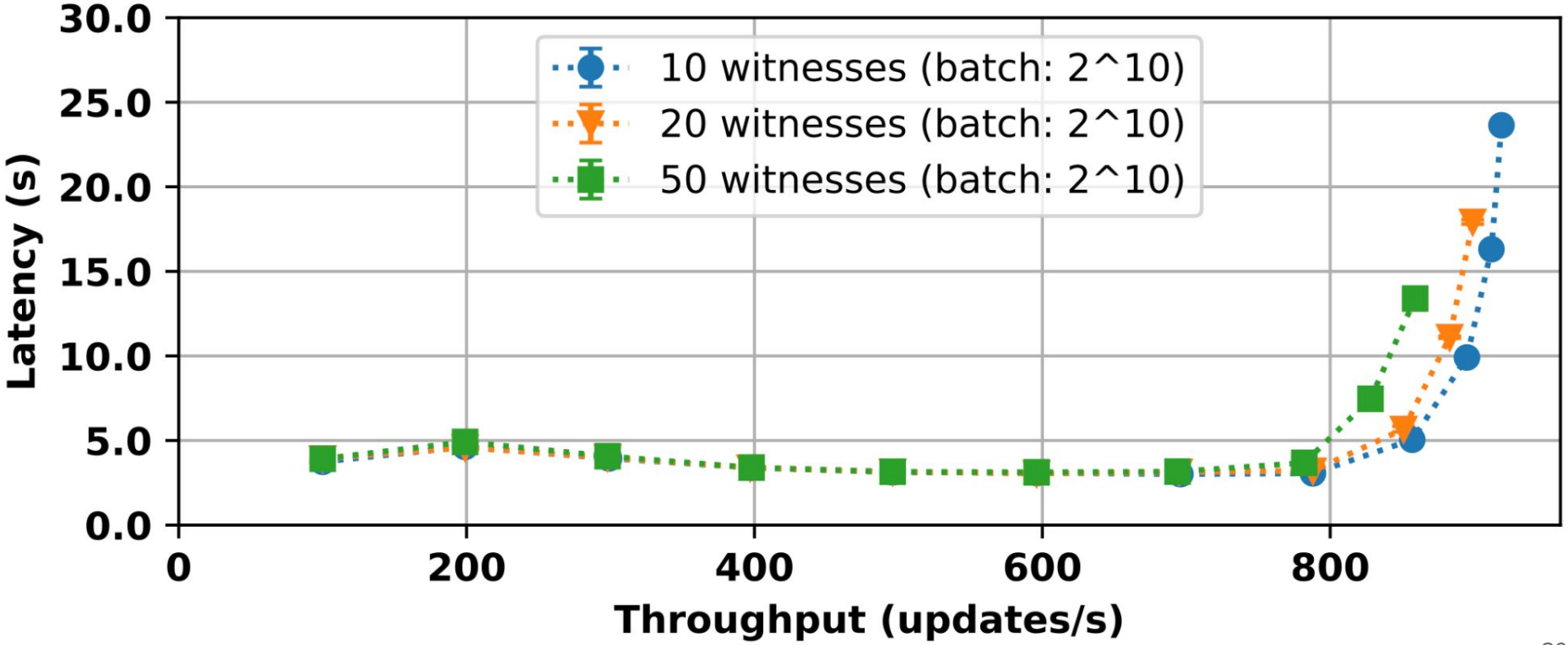


Fig. 4: Illustration of the key update protocol.

Consensus-less Strong Consistency Performance



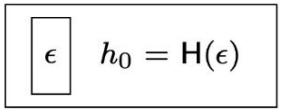
Thank You

Thank you!

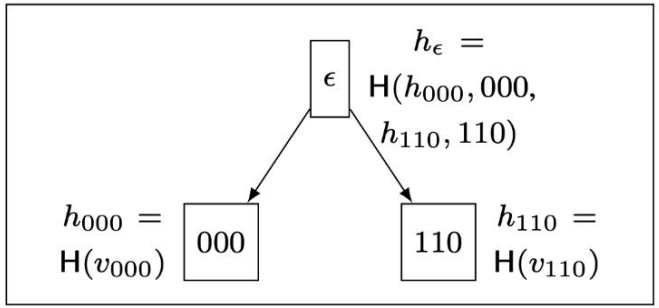
- Thanks to my awesome collaborators!
- Find the paper on the NDSS website! (more details in full version: https://eprint.iacr.org/2023/081.pdf)
- **Open source implementations:** linked in the paper.

Appendix
(useful for several FAQs)

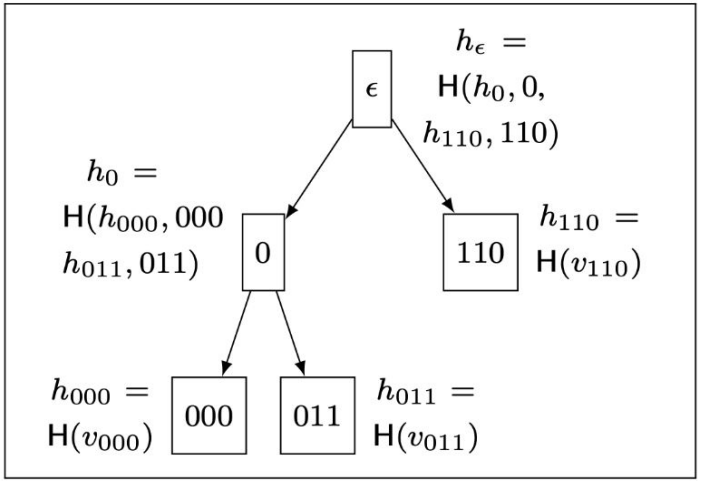
SEEMless Data Structure: aZKS



Epoch 0

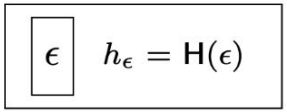


Epoch 1: After inserting label-value pairs $(000, v_{000})$ and $(110, v_{110})$.



Epoch 2: After inserting label-value pair $(011, v_{011})$.

Parakeet Data Structure: oZKS



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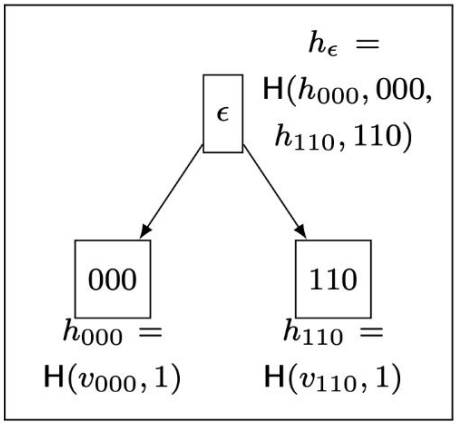

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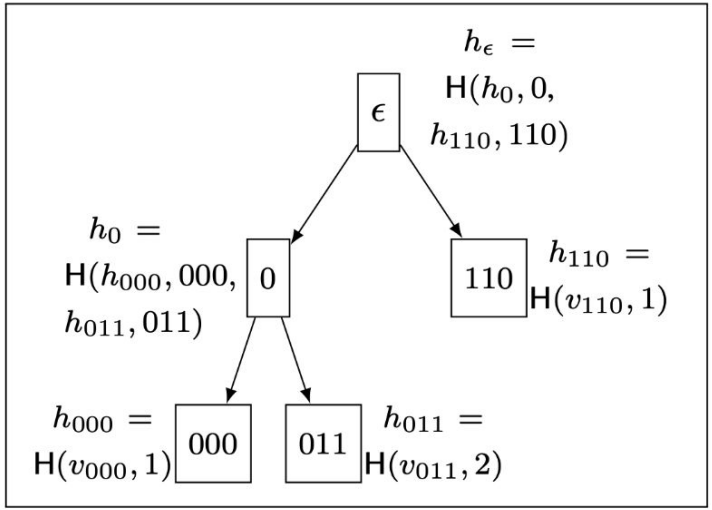

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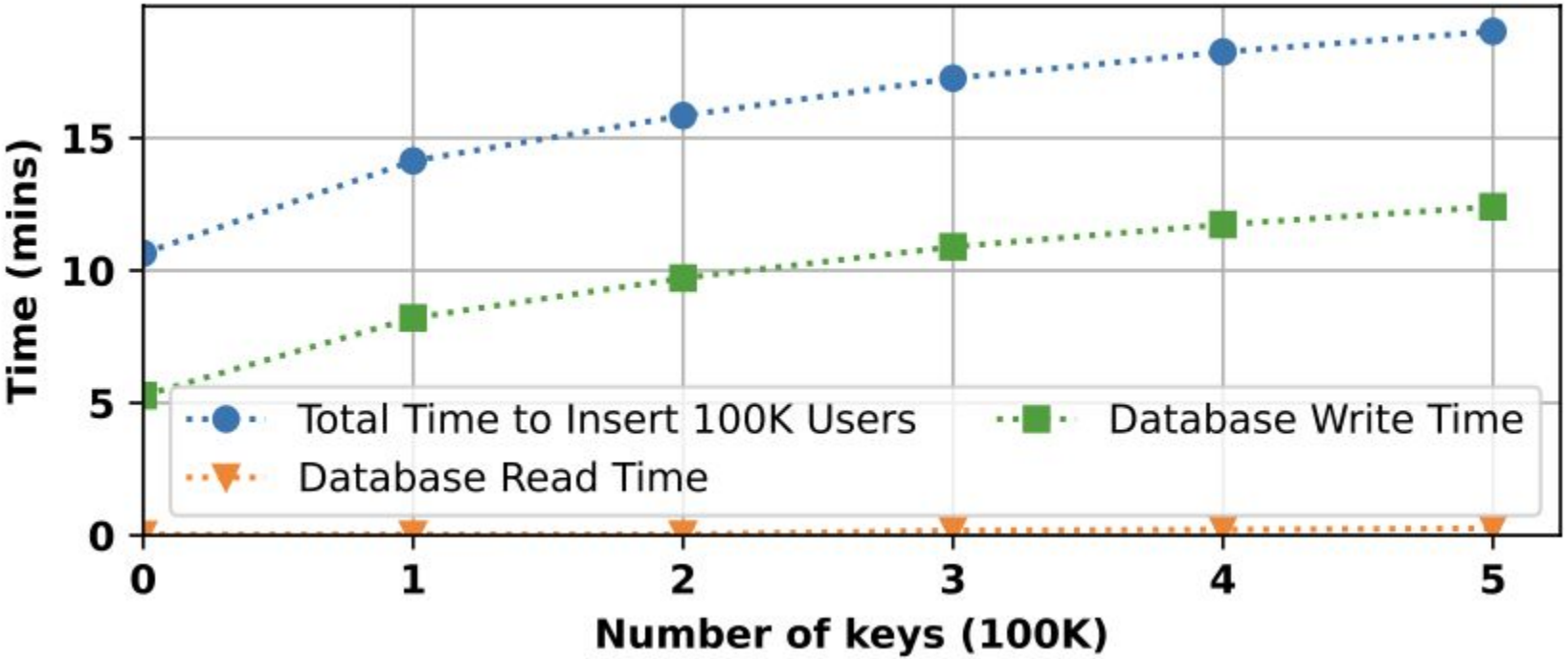
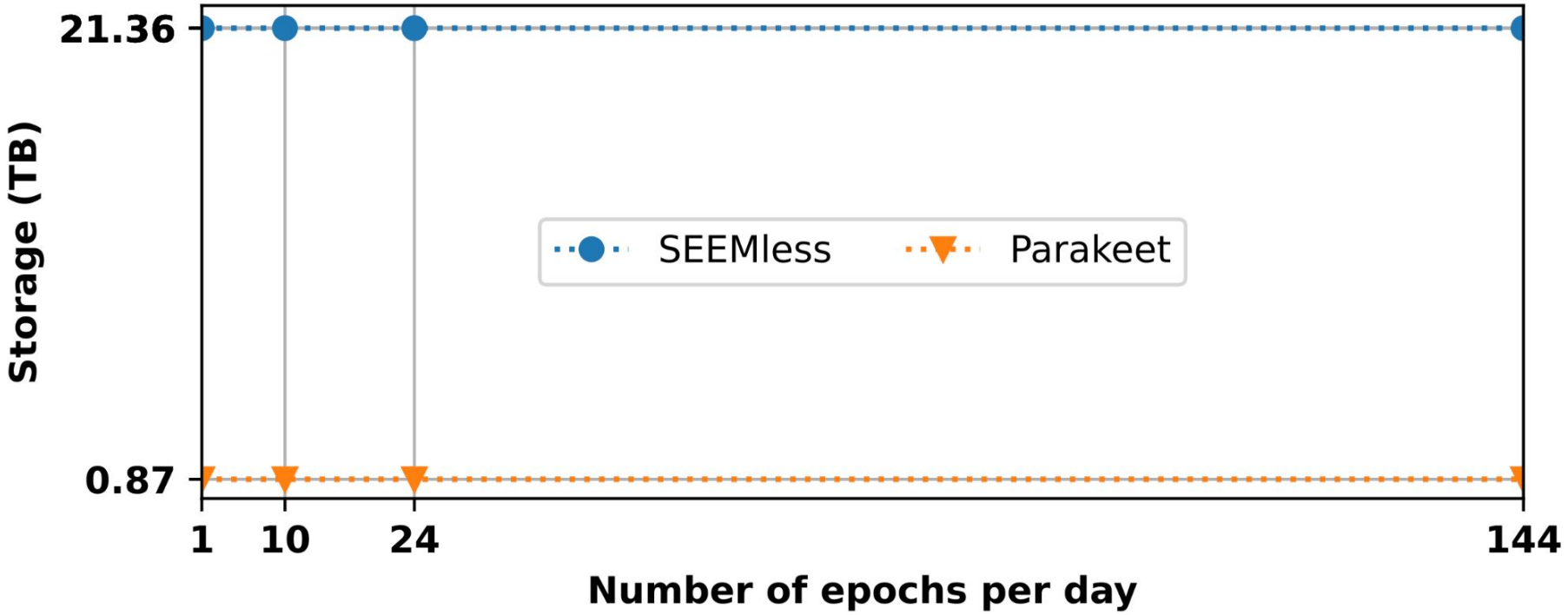
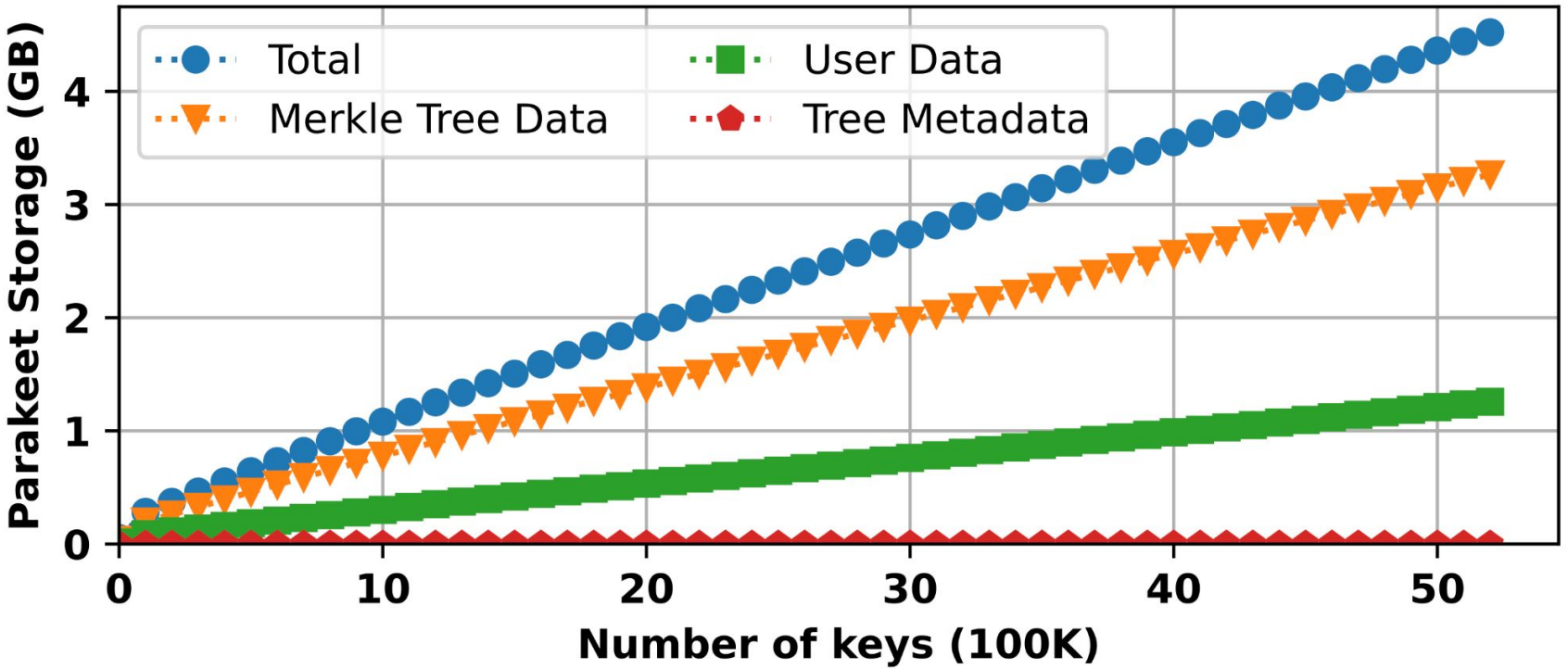
Update Time Breakdown



Comparing Storage costs



Storage Breakdown



Entries for a User

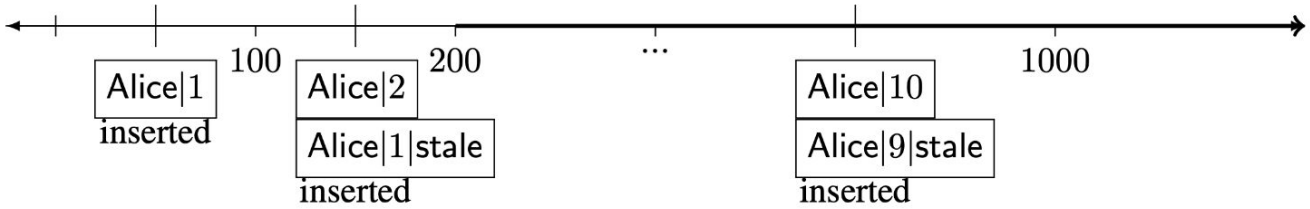
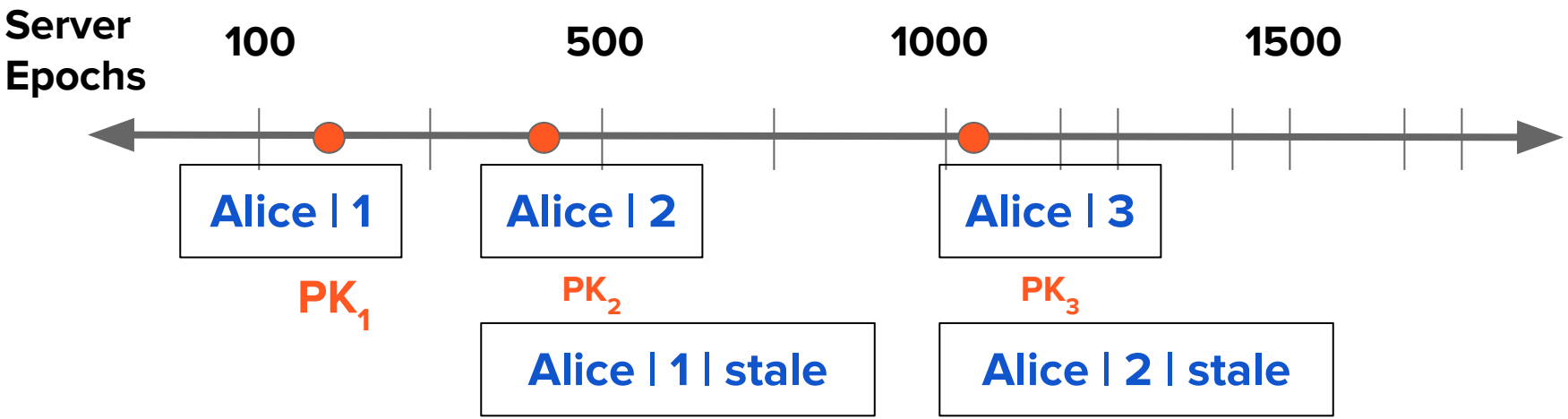


Fig. 3: An example of labels corresponding to user Alice's key updates. Since Alice has changed their key enough times since their initial entry into the system and epochs before epoch 200 are considered *old enough*, Alice|1, Alice|1|stale can be deleted.

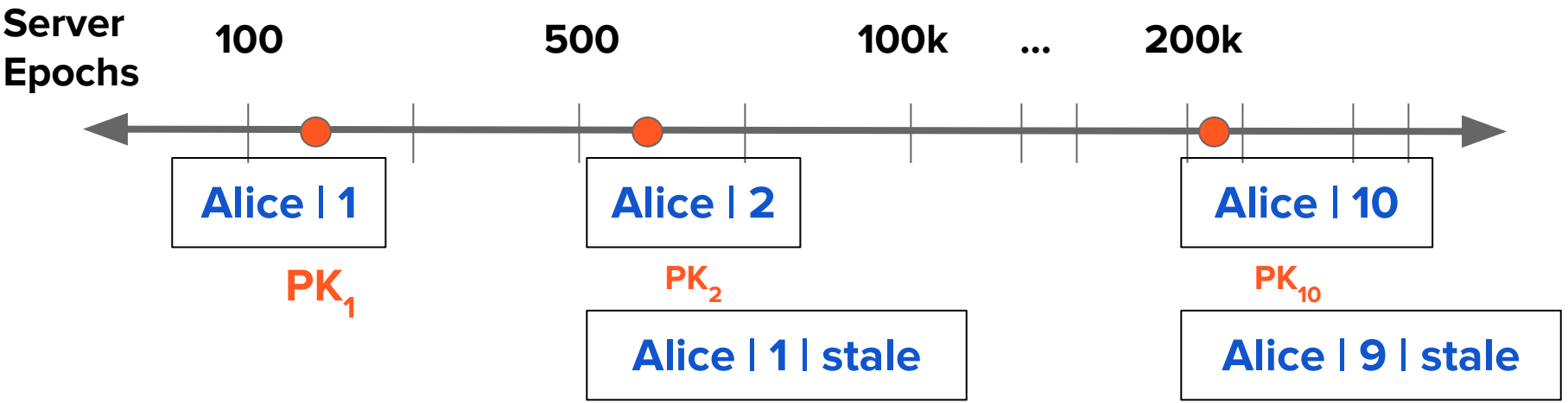
Sharing a small commitment: Blockchains?

- Could post the commitment in a smart contract or OP_RETURN on bitcoin.
- Must trust the blockchain and its code.
- Even “light” clients could be too heavyweight.
- If billions of users query, could end up flooding the network with queries!
- Proposed mitigation: header relay network.
  - Similar to having a few nodes serving the commitment (i.e. blockchain view).
  - Might as well, just have the nodes agree on and serve the commitment...
  - Custom blockchain?

Commitments for One User



Commitments for One User Over Time



(In)Valid Deletions