# IronDict: Transparent Dictionaries from Polynomial Commitments

Hossein Hafezi  Alireza Shirzad  Benedikt Bünz  Joseph Bonneau



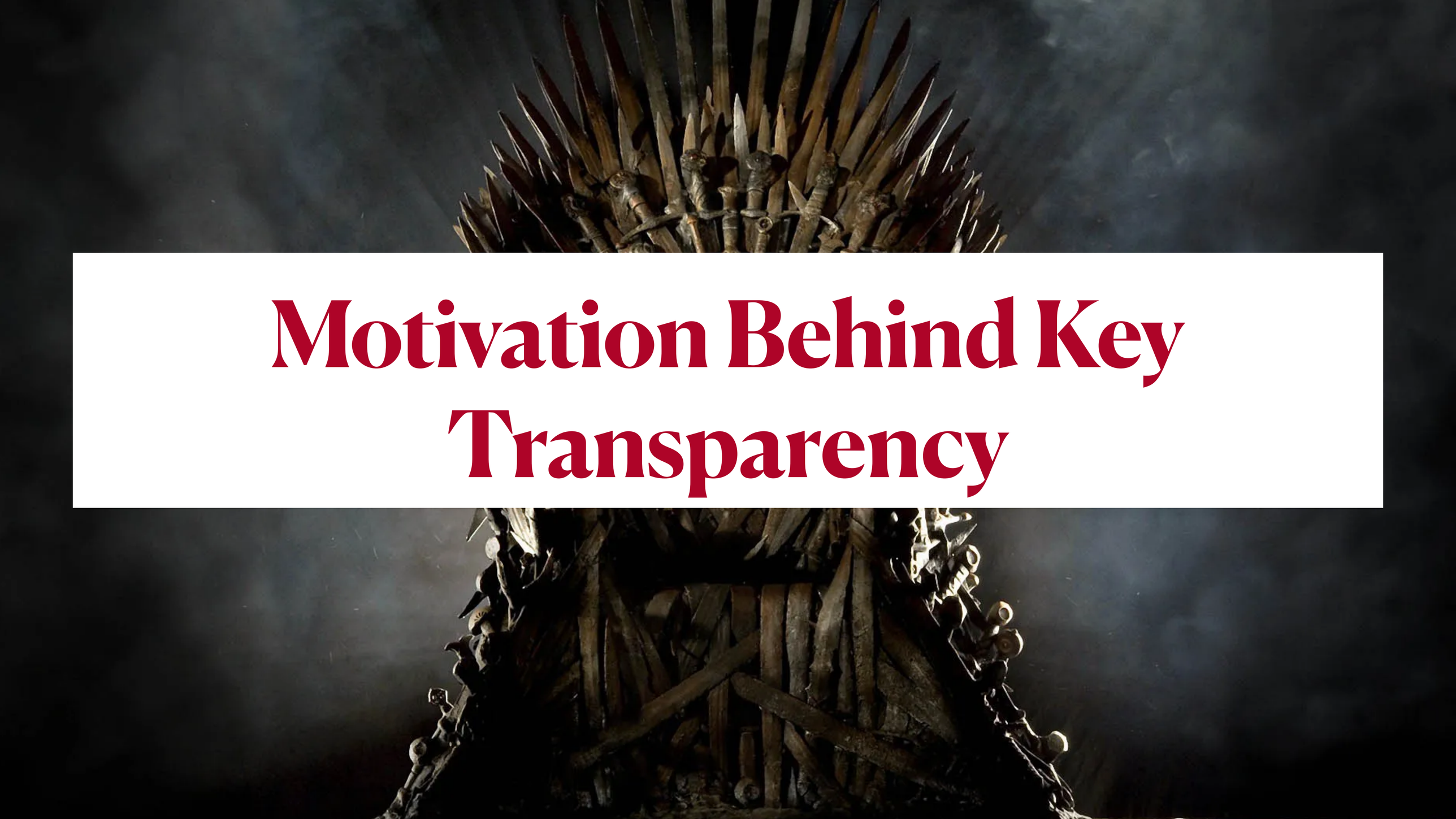






# What does this talk concern?

- A line of work on building key transparency via polynomial commitments
    - IronDict: https://ia.cr/2025/1580
    - Aegon: https://ia.cr/2026/1681
    - pq-Aegon: coming on Eprint soon!
- Check out the talks given at Microsoft Research on IronDict and Aegon for more details



# Motivation Behind Key Transparency

# End-to-End Encrypted Messaging



$(pk_{\text{Jon}}, pk_{\text{Ygritte}})$



$(pk_{\text{Jon}}, pk_{\text{Ygritte}})$



# End-to-End Encrypted Messaging



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**The service provider only transmits ciphertexts and cannot decrypt them**



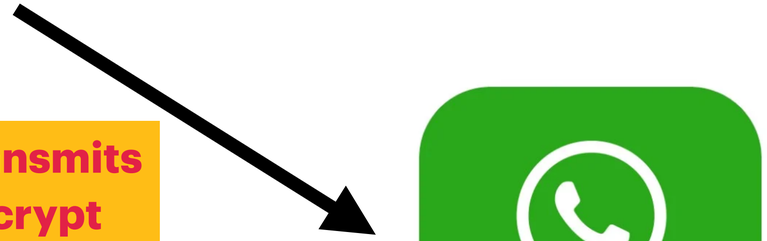
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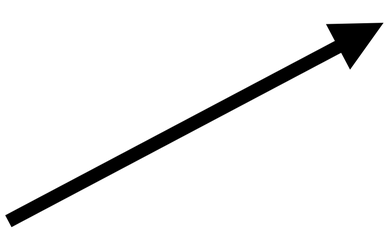
$(pk_{\text{Jon}}, pk_{\text{Ygritte}})$



$(pk_{\text{Jon}}, pk_{\text{Ygritte}})$





**The service provider only transmits ciphertexts and cannot decrypt them**

**How do users get each other public keys for example from a phone number?**

# End-to-End Encrypted Messaging



$(pk_{\text{Jon}}, pk_{\text{NK}})$



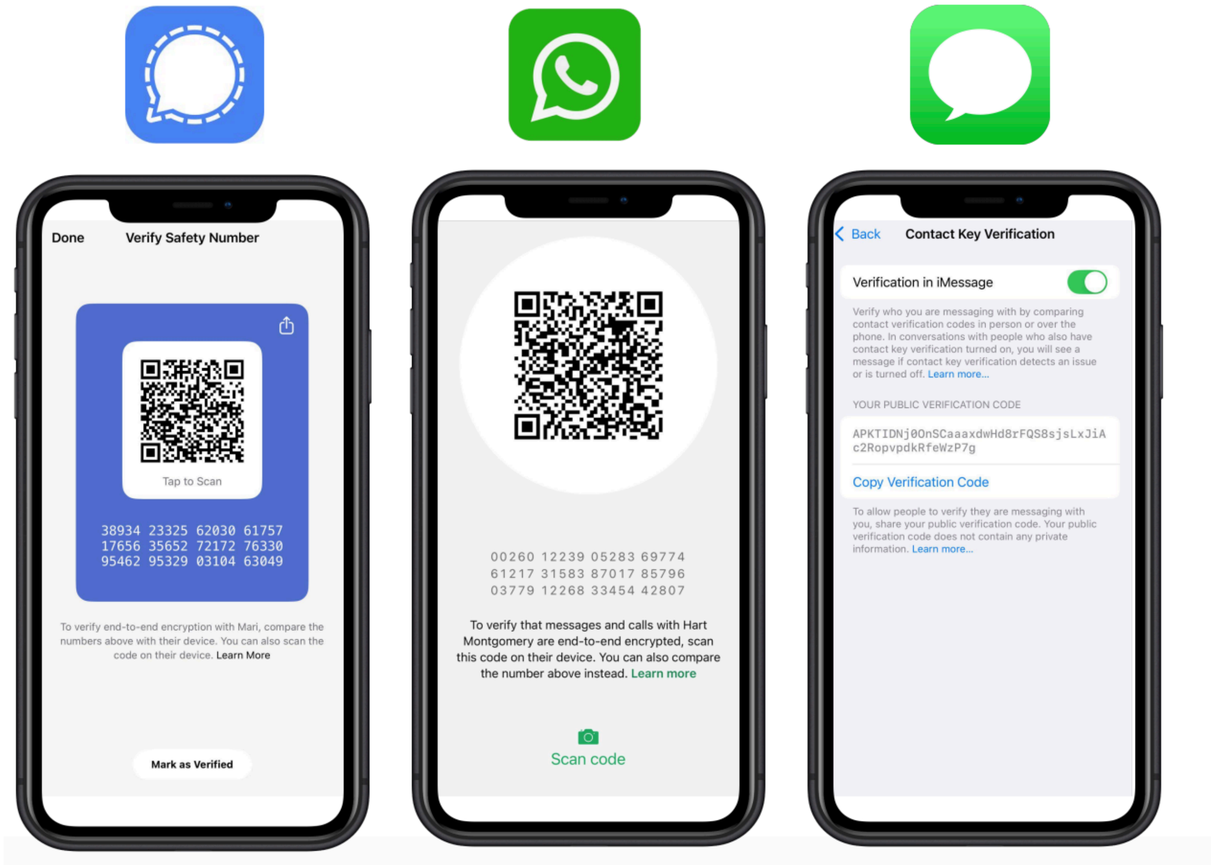
$(pk_{\text{Jon}}, pk_{\text{NK}})$




Give Jon a malicious public key


“You know nothing, Jon Snow.”

# Traditional Solution: Out-of-Band Verification



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# Key Transparency: CONIKS [Mel+15]








WhatsApp

# Key Transparency: CONIKS [Mel+15]






Periodically post

Signed commitments

to directory



WhatsApp

# Key Transparency: CONIKS [Mel+15]








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$pk_{\text{Ygritte}}, \pi$

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Verify pk is consistent with the commitment to the bulletin board






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WhatsApp

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Periodically post

Signed commitments

to directory

**AUTOMATED SOLUTION: no manual effort for Jon and Ygritte**

$pk_{\text{Ygritte}}, \pi$

WhatsApp

$pk_{\text{Ygritte}}, \pi$

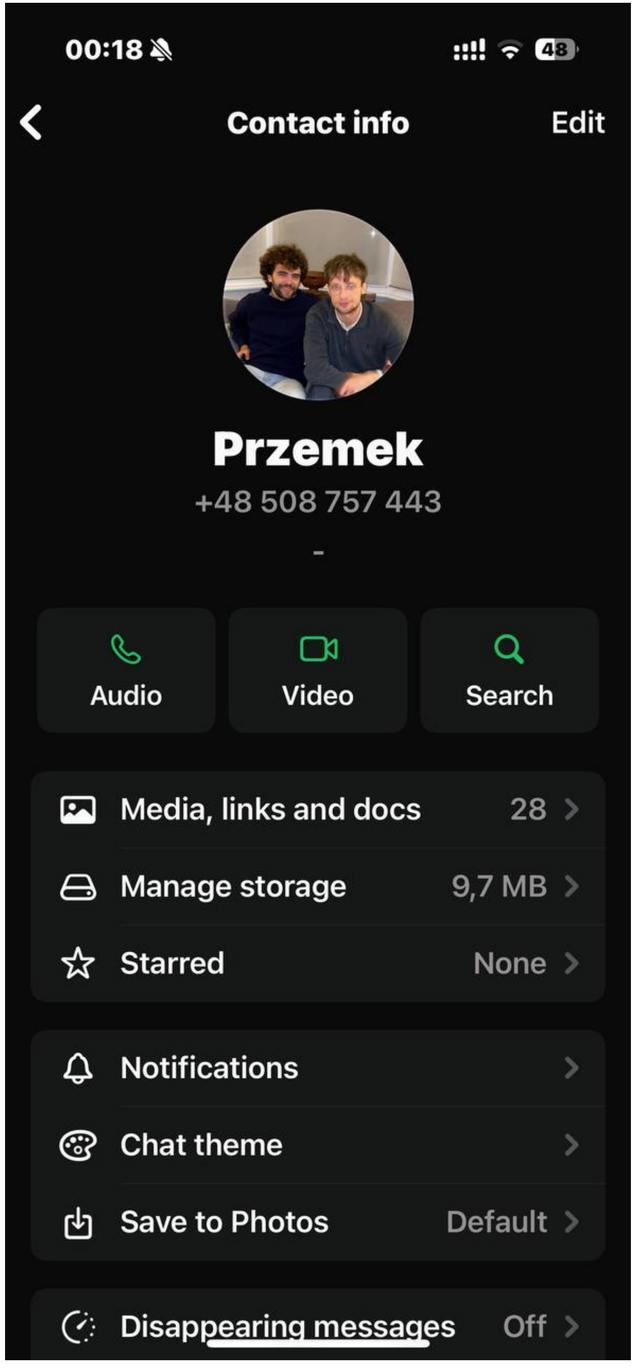
# Key Transparency Model

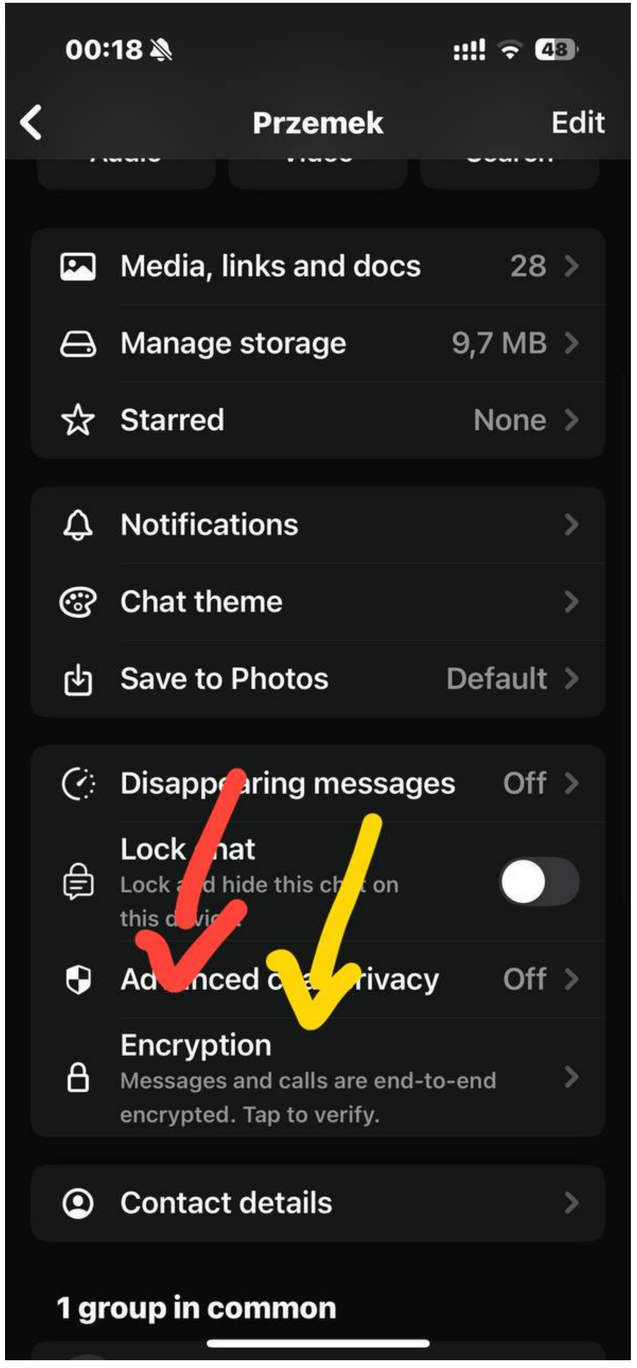


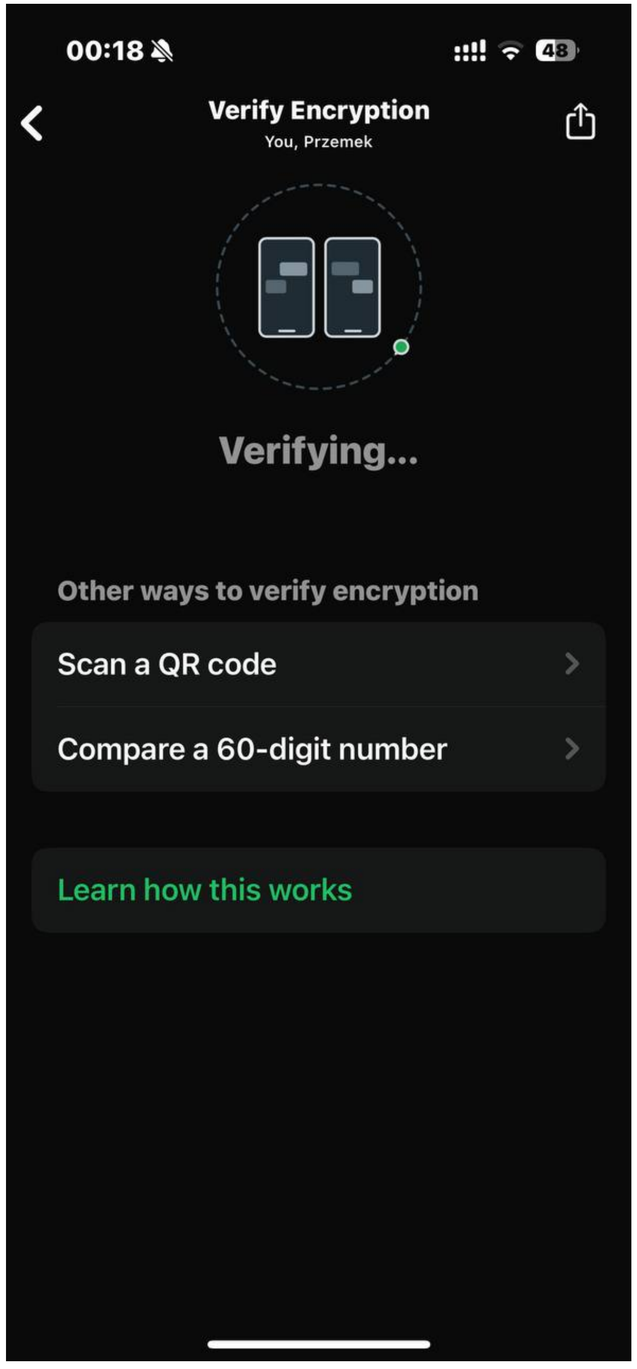


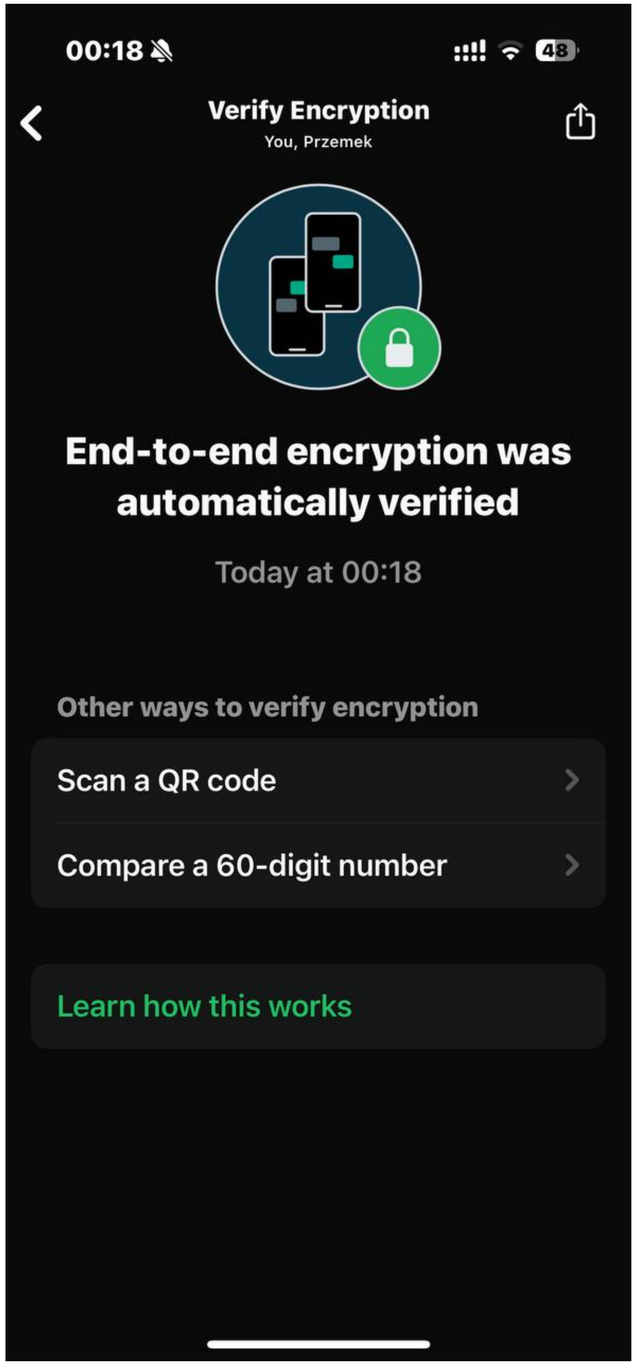





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Przemek
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Video
Search
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Manage storage 9,7 MB
Starred None
Notifications
Chat theme
Save to Photos Default
Disappearing messages Off

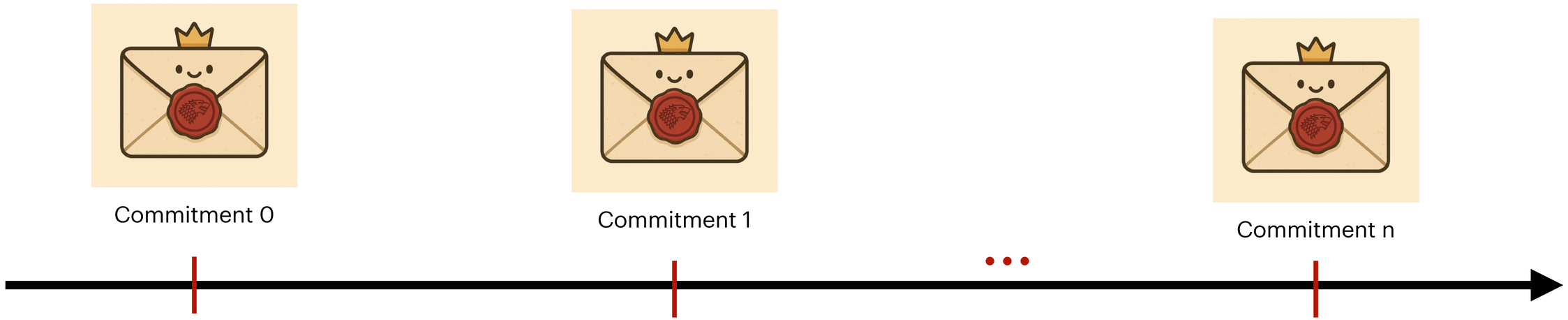

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Disappearing messages Off
Lock chat
Advanced chat privacy Off
Encryption
Messages and calls are end-to-end encrypted. Tap to verify.
Contact details
1 group in common


00:18
Verify Encryption
You, Przemek
Verifying...
Other ways to verify encryption
Scan a QR code
Compare a 60-digit number
Learn how this works


00:18
Verify Encryption
You, Przemek
End-to-end encryption was automatically verified
Today at 00:18
Other ways to verify encryption
Scan a QR code
Compare a 60-digit number
Learn how this works

# Key Transparency Scheme

- Key transparency scheme consists of a server that at every epoch publishes the new commitment to the directory along with auxiliary data (invariance proof)



# Key Transparency Scheme



Jon

(I) What is Ygritte's latest public key?

Lookup

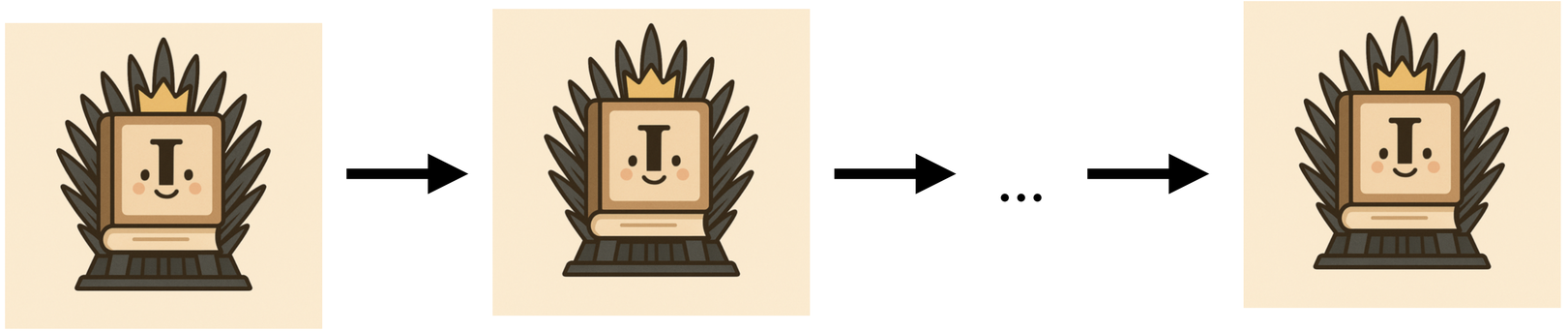
(II) My key hasn't changed since last year?

Proof of consistency

WhatsApp

# Necessity of Proof of Consistency

**Assume Jon is offline from state i+1 to state j-1**



State i

State i+1

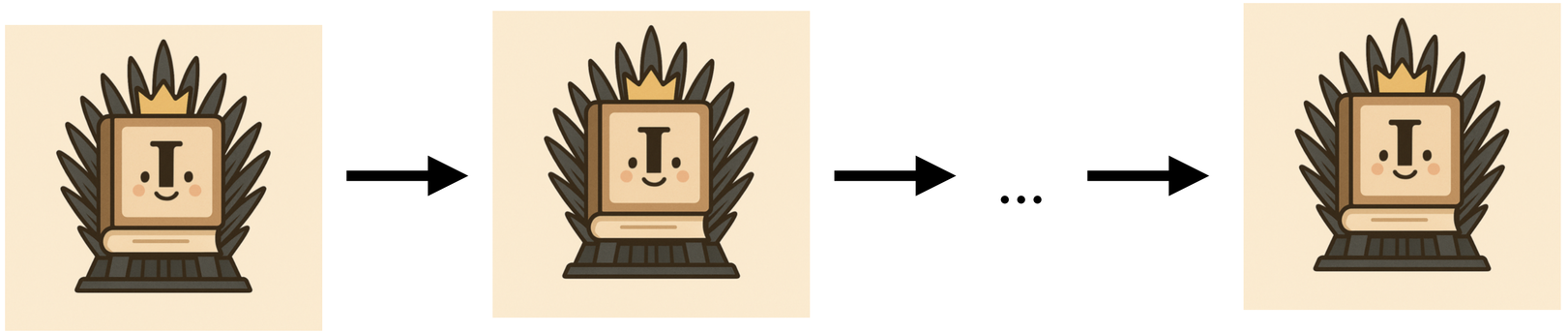
State j





# Necessity of Proof of Consistency

**Assume Jon is offline from state i+1 to state j-1**



State i

State i+1

State j

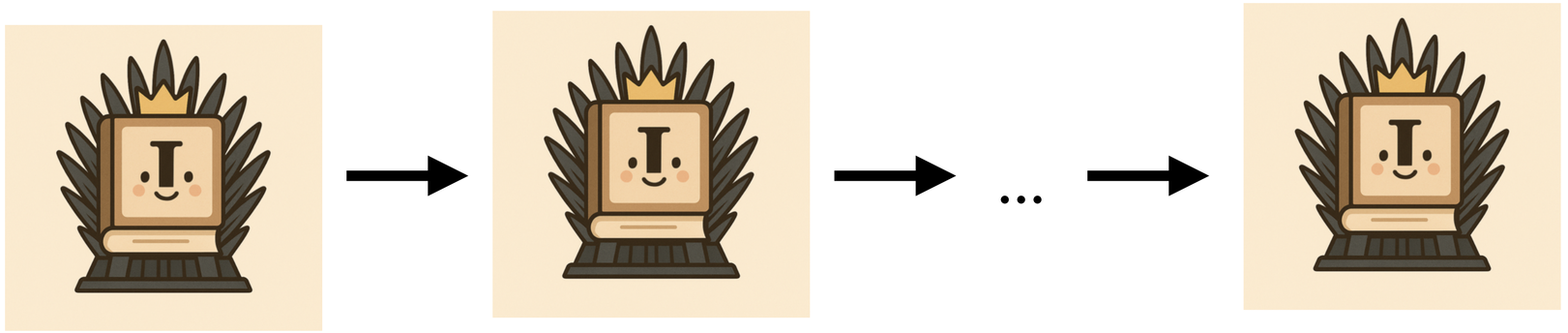






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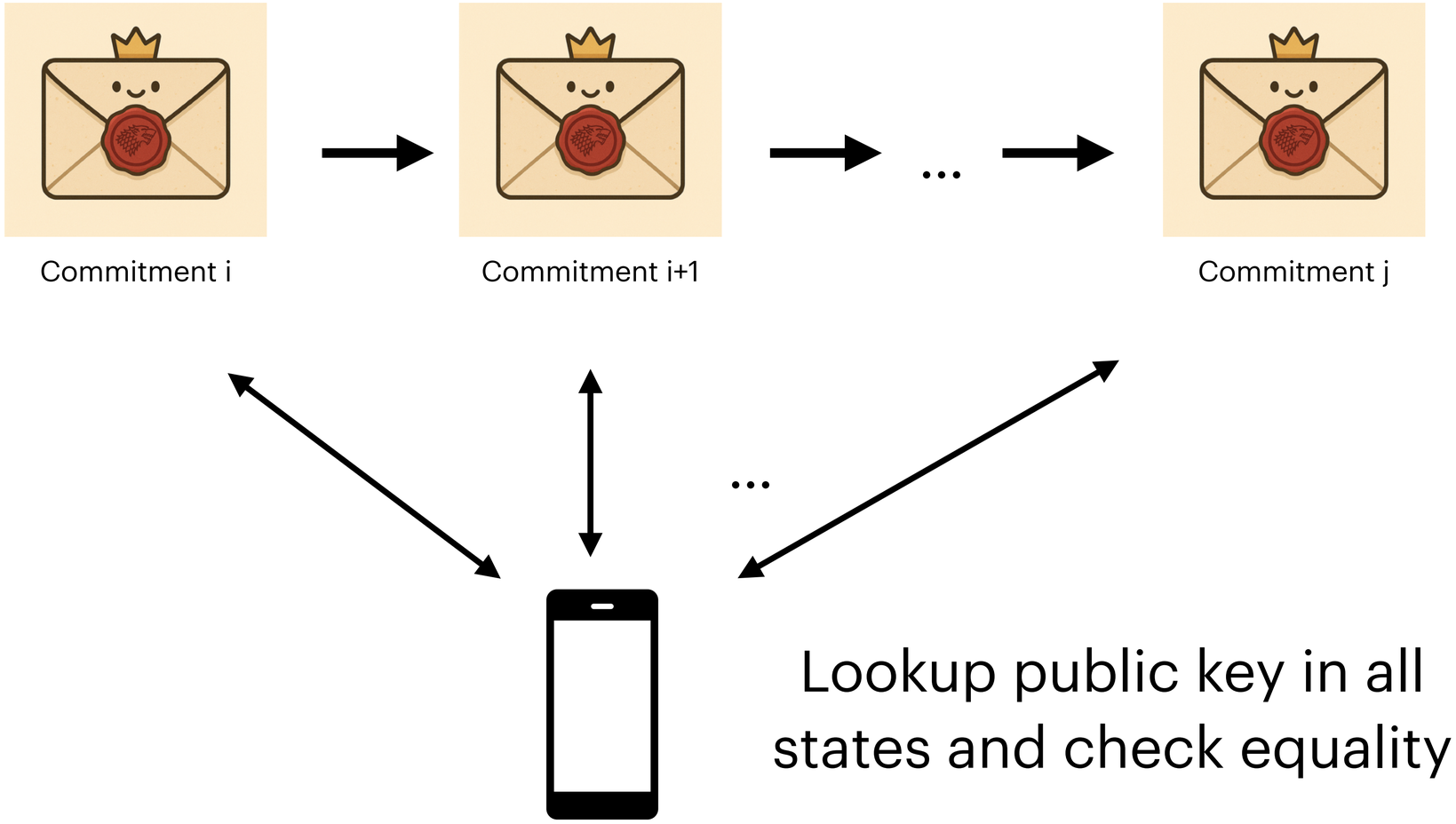


Request a proof of consistency from epoch i to epoch j

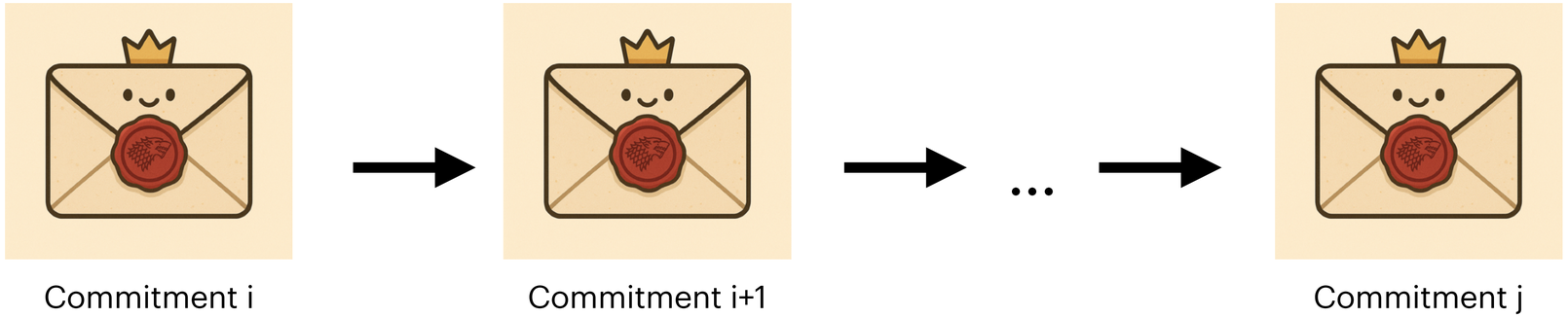
# Different Solutions to Proof of Consistency

- Naively performing lookup for every epoch, e.g. CONIKS [Mel+15]
- Version Invariant, e.g. SEEMless [Cha+19], Parakeet [Mal+23], Optiks [Len+24]
- Random Version Invariant, e.g. IronDict [Haf+26] and Aegon [Haf+26]

# Proof of Consistency: Naive Solution [Mel+15]

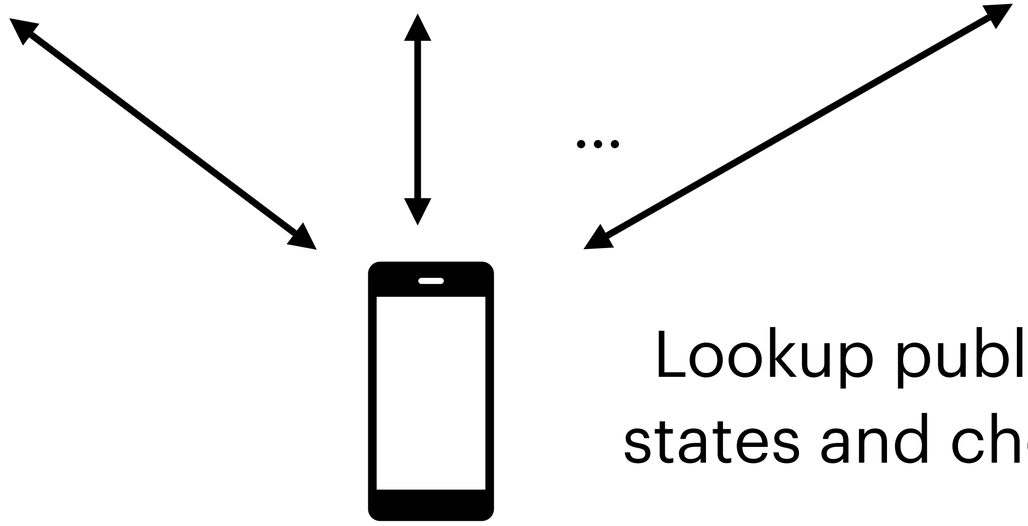


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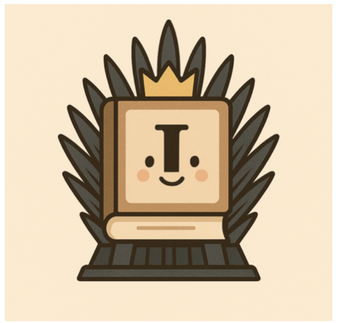




Lookup public key in all states and check equality

# Version Invariant [Cha+19, Mal+23, Len+24]

i



state i

$(pk_{\mathsf{Jon},i}, v_i)$



j



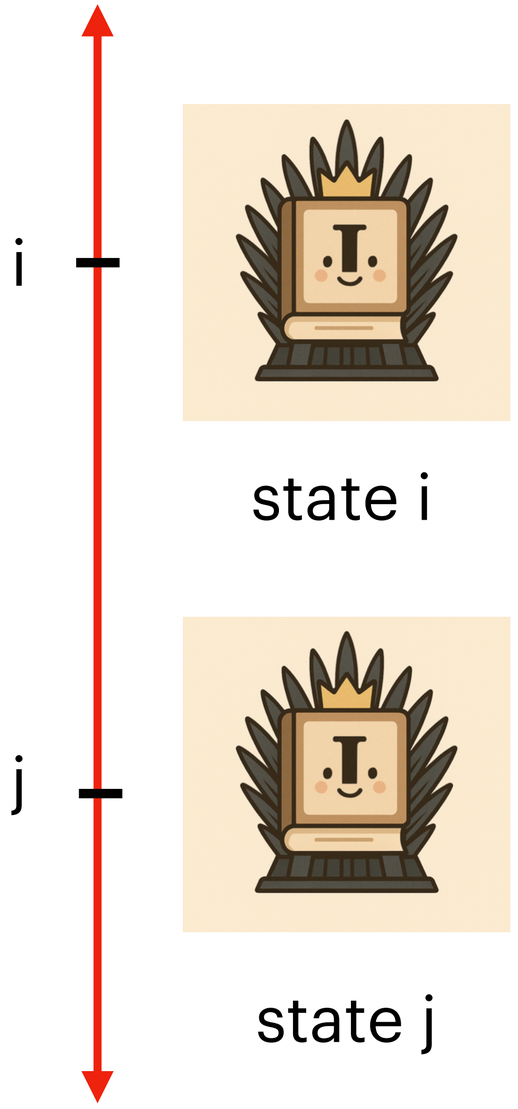
state j

$(pk_{\mathsf{Jon},j}, v_j)$



time

# Version Invariant [Cha+19, Mal+23, Len+24]



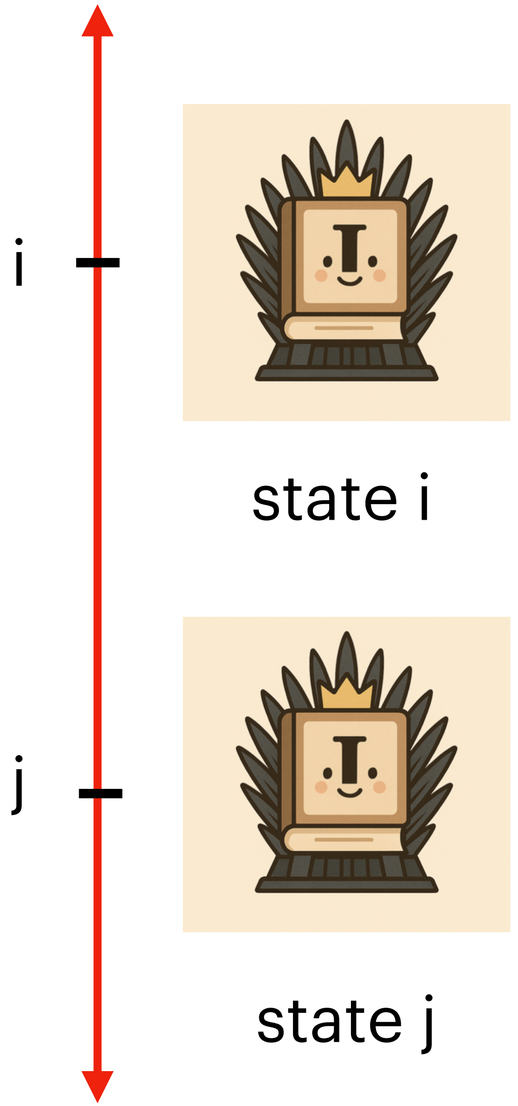

$(pk_{\mathsf{Jon},i}, v_i)$

$(pk_{\mathsf{Jon},j}, v_j)$

proof of consistency from epoch i to j

$$\iff v_i = v_j$$

# Version Invariant [Cha+19, Mal+23, Len+24]






state i

$(pk_{\mathsf{Jon},i}, v_i)$



state j

$(pk_{\mathsf{Jon},j}, v_j)$

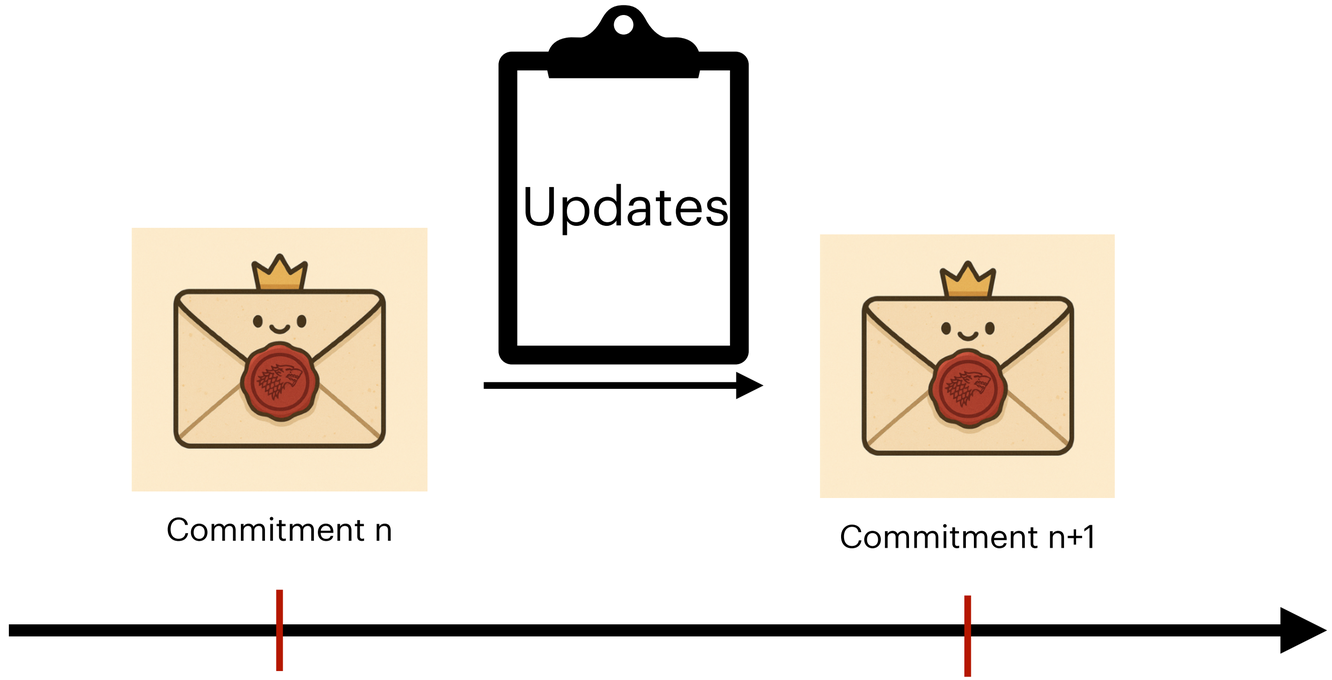
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**How to audit the version invariant?**

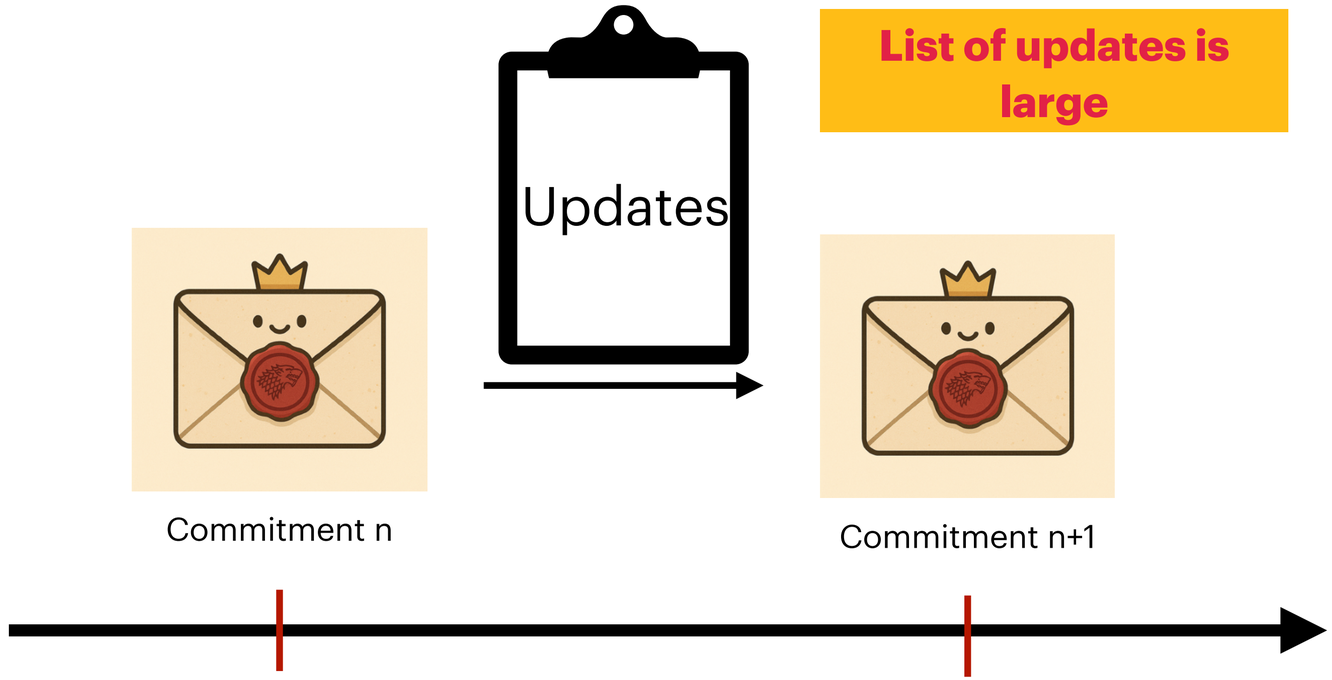
# Auditing Version Invariant [Cha+19, Mal+23, Len+24]

- Server publishes invariance proof == the list of updates.
- ***Auditors*** verify the updates have been appended correctly.



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# Drawbacks of Existing Deployed Schemes

# Main Challenges of Existing Deployed Schemes? (SEEMless [Cha+19], Parakeet [Mal+23], Optiks [Len+24])

- Self-Auditability
- Perfect Privacy
- History Pruning

# Challenge I: Self-Auditability

- Proof of invariance is large ==> linear in the number of updates in the epoch.

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**Attempts to make the proof succinct using SNARKs (e.g., Verdict [Tzi+22] and Hekaton [Ros+24]) ==> high hash-function costs in circuits limit scalability.**

# Challenge II: Perfect Privacy

- Privacy is crucial in the context of key transparency:
  - Lookups shouldn’t reveal pattern of changing keys of users.
  - Otherwise an adversary observing a user doesn’t change their key regularly, makes it a potential target for them.

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- Privacy is crucial in the context of key transparency:
  - Lookups shouldn't reveal pattern of changing keys of users.
  - Otherwise an adversary observing a user doesn't change their key regularly, makes it a potential target for them.
- Tree-based solutions do not offer perfect privacy.
  - SEEMless reveals the last time a key was updated during a lookup.

# Challenge III: History Pruning

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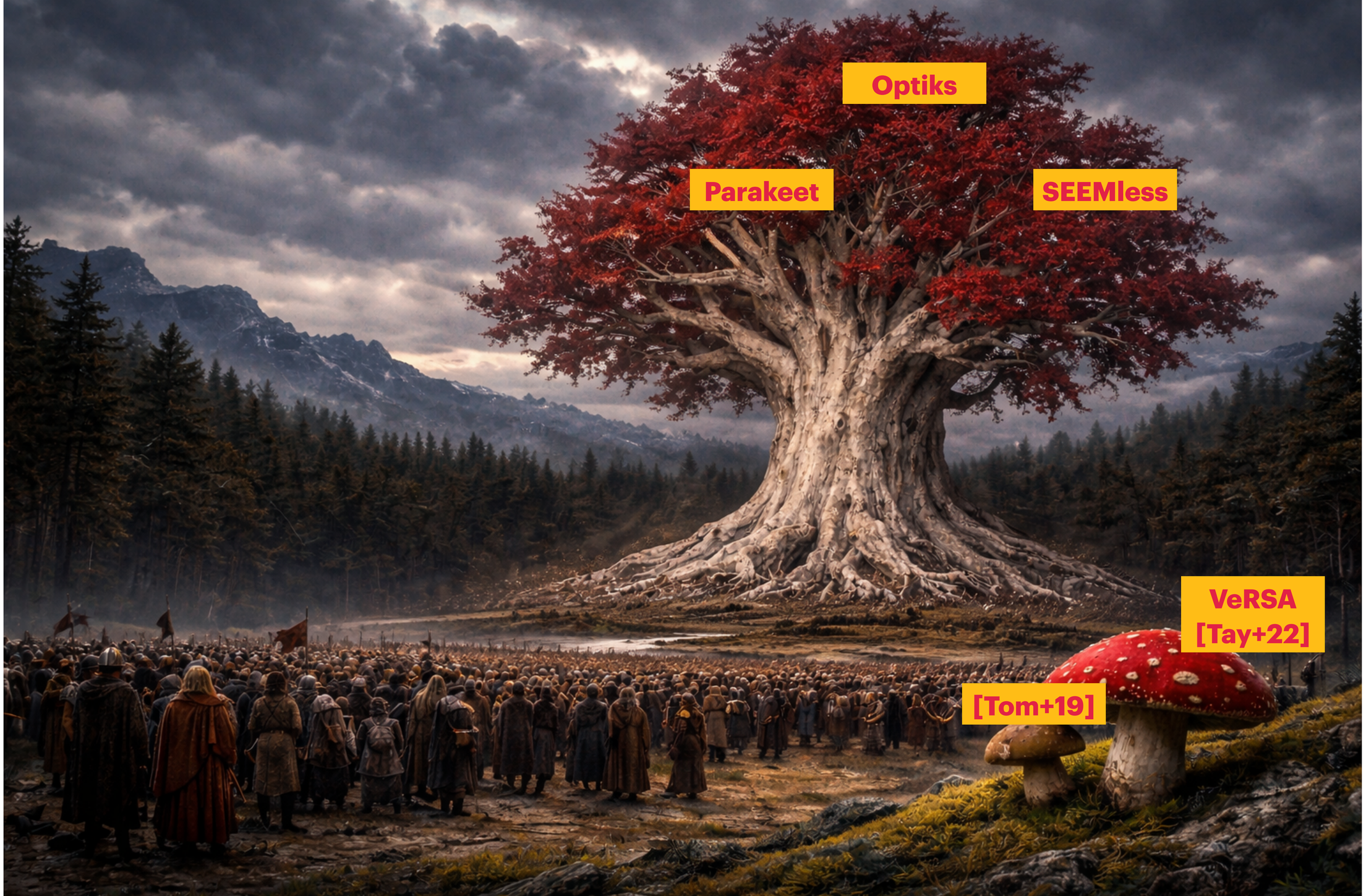
# Challenge III: History Pruning

- The tree-based models (except for CONIKS) are based on append-only trees.
- All unnecessary historical data are kept in the tree and its size grows indefinitely.
- WhatsApp has a user base of 3-4 billion, but its tree size is more than 100 billion.



# Our Proposed Schemes: IronDict and Aegon


Optiks
Parakeet
SEEMless


Optiks
Parakeet
SEEMless
VeRSA
[Tay+22]
[Tom+19]


Optiks
Parakeet
SEEMless
VeRSA
[Tay+22]
[Tom+19]


IronDict / Aegon
based on polynomials
Optiks
Parakeet
SEEMless
VeRSA
[Tay+22]
[Tom+19]

# IronDict

- **Self-auditability:** constant proof size, 8 kB for dictionary of size 1 billion.

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- **Self-auditability:** constant proof size, 8 kB for dictionary of size 1 billion.
  - **Fast-forwarding:** Check a single audit proof and verify the whole history
  - Self-auditability without fast-forwarding is pointless.
- **Perfect privacy**


AEGON
IRONDICT
Requirement of a Linear-Sized Setup
High Epoch Latency
Storage Inefficiency
Not Horizontally Scalable

# Two main techniques in IronDict and Aegon

- Open addressing to assign string labels to points on the Boolean hypercube
- Random linear combination technique

# Random Version Invariant of IronDict and Aegon

$$\mathrm{Dict}_i = (pk_1^{(i)}, pk_2^{(i)}, \ldots, pk_N^{(i)}),$$

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Ghost key attack : $\sum_{i<k\leq j} \Delta_k[t] = 0$ and $\exists\, i < i_0 \leq j : \Delta_{i_0}[t] \neq 0$

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**Use randomness so the differences do not cancel each other out**

# Random Version Invariant of IronDict and Aegon

$$\text{Rand vector} : \text{Rand}_n = \text{Dict}_0 + \sum_{i \leq n} r_i \cdot \Delta_i \equiv \text{Rand}_{n+1} = \text{Rand}_n + r_{n+1} \cdot \Delta_{n+1}$$

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$$\text{proof of consistency from epoch i to epoch j} \iff \text{Rand}_i[t] = \text{Rand}_j[t]$$

$$\text{auditor's task} \implies \text{ensure Rand}_n \text{ is computed correctly}$$

# See Numbers!

| | Irondict | Aegon | SEEMLESS + Parakeet |
|---|---|---|---|
| **Epoch Latency** | **15 min** | **60 s** | **60 s** |
| **Throughput** | **~1000 update/s** | **~1000 update/s** | **~1000 update/s** |
| **Lookup proof / verification** | **5 KB / 30 ms** | **5 KB / 30 ms** | **2-4 KB / 0.1 ms** |
| **Lookup latency (server)** | **30 ms** | **5.6 ms** | **0.5 s** |
| **Audit proof / verification** | **8 KB / 35 ms** | **7.5 KB / 15 ms** | **80 MB / 0.7s** |

# Concrete Instantiation?

- Aegon = generic over any polynomial commitment schemes. We instantiate it with **KZH** [Kad+25] that requires a powers-of-tau setup ==> MPC ceremony setup

KZH-Fold:
Accountable Voting from Sublinear Accumulation

George Kadianakis[1], Arantxa Zapico[2], Hossein Hafezi[3], and Benedikt Bünz[4]

[1,2]Ethereum Foundation
[3,4]New York University

- Future Work: Design alternative polynomial commitments without a trusted setup.