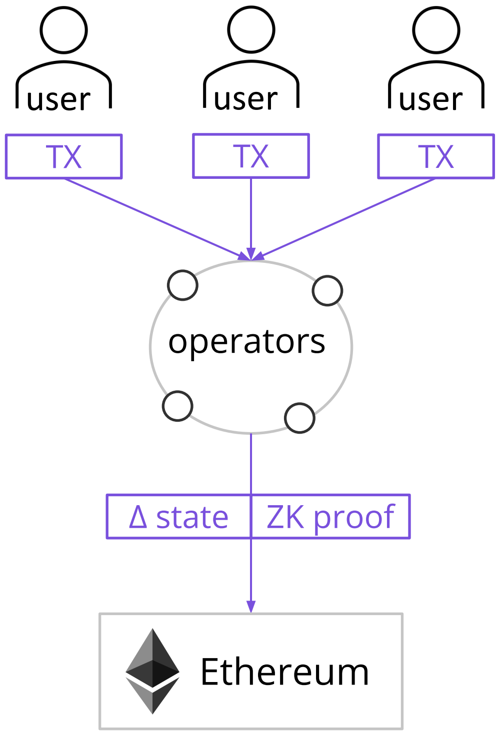
Using a hybrid UTXO and account-based state model in a ZK rollup

Bobbin Threadbare
Polygon Miden

Goal

Build a **scalable decentralized** rollup with **privacy-enabling** architecture

What is a decentralized Rollup?



Security inherited from Ethereum

Separate L2 chain with its own consensus mechanism

Permissionless set of operators

Challenges of a decentralized rollup

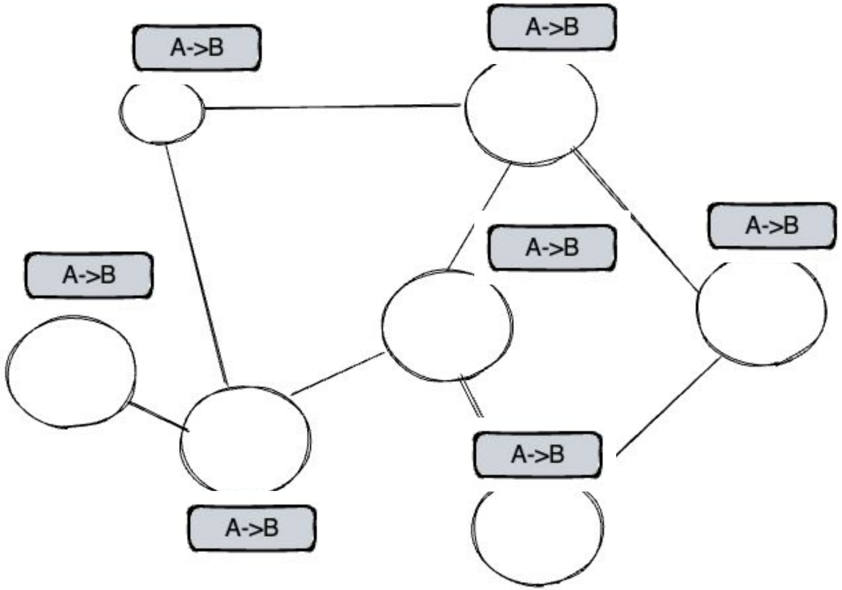
Consensus mechanism

Execution bloat

State bloat

Topic of this talk

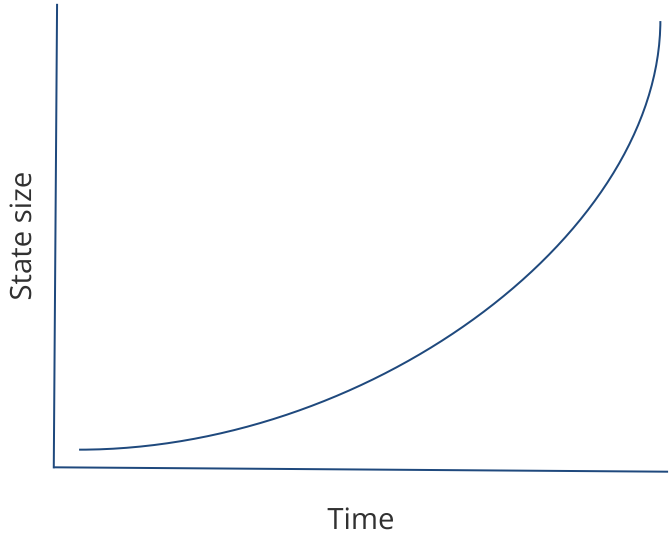
What is execution bloat?



All transactions executed by the network

- Block producers execute all transactions in a block
- All other nodes re-execute all transactions in a block

What is state bloat?



State size grows with time

- Nodes need full state to validate blocks
- Nodes need full state to produce new blocks

Why are execution and state bloat bad?

Execution bloat
State bloat

Centralization

Need powerful machines

Less privacy

Everyone sees everything

Not sustainable

Ever growing state

What we want to achieve

Minimize execution bloat		Minimize state bloat
• Transactions executed only once	**Can be done with ZKPs**	• No need to know the full state to validate blocks
• Transactions executed concurrently by distinct actors	**Requires concurrent state model**	• No need to know the full state to produce blocks

State model options

Account-based state

Great for expressive smart contract

Not great for concurrent transaction execution

Bad for anonymity

UTXO-based state

Great for concurrent transaction execution

Needed for anonymity

Not great for expressive smart contracts

Our approach

Account model +

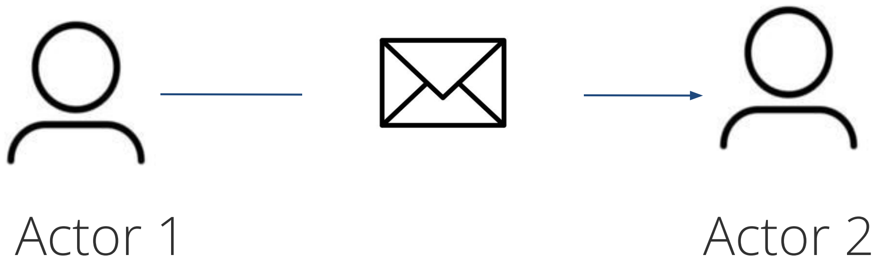
UTXO model +

ZK proofs

→ **Actor-based model with concurrent off-chain state**

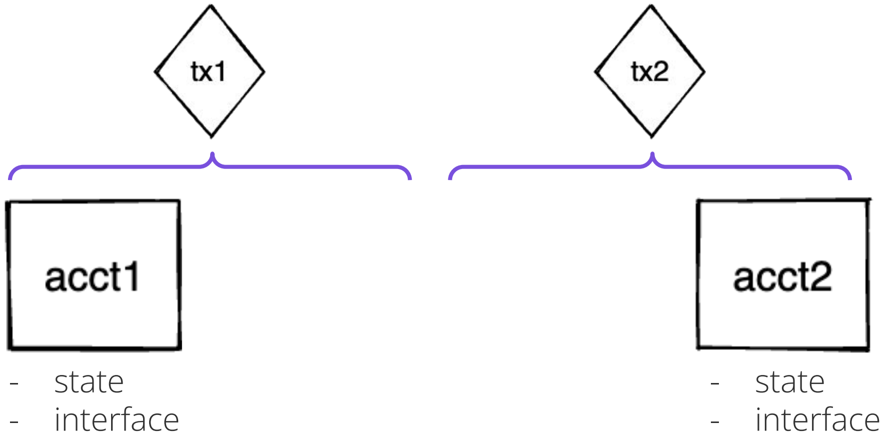
transaction model

Actor model



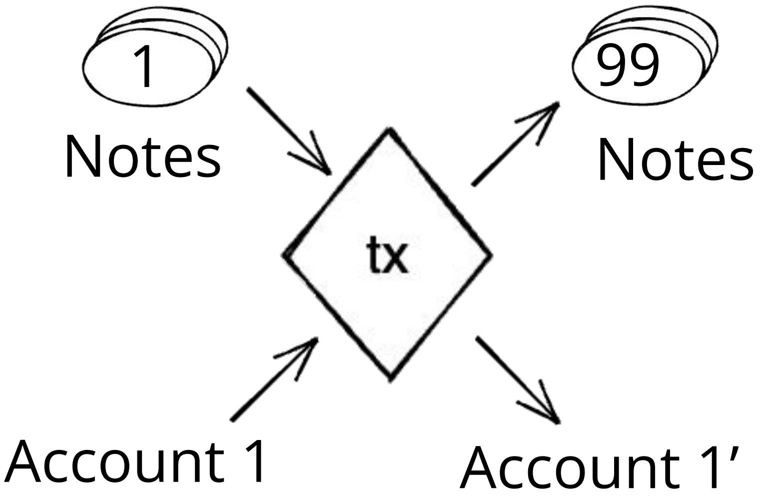
- Actors are state machines with “inboxes”
- Actors communicate via message passing
- Messages are produced and consumed asynchronously

Actor model in Miden



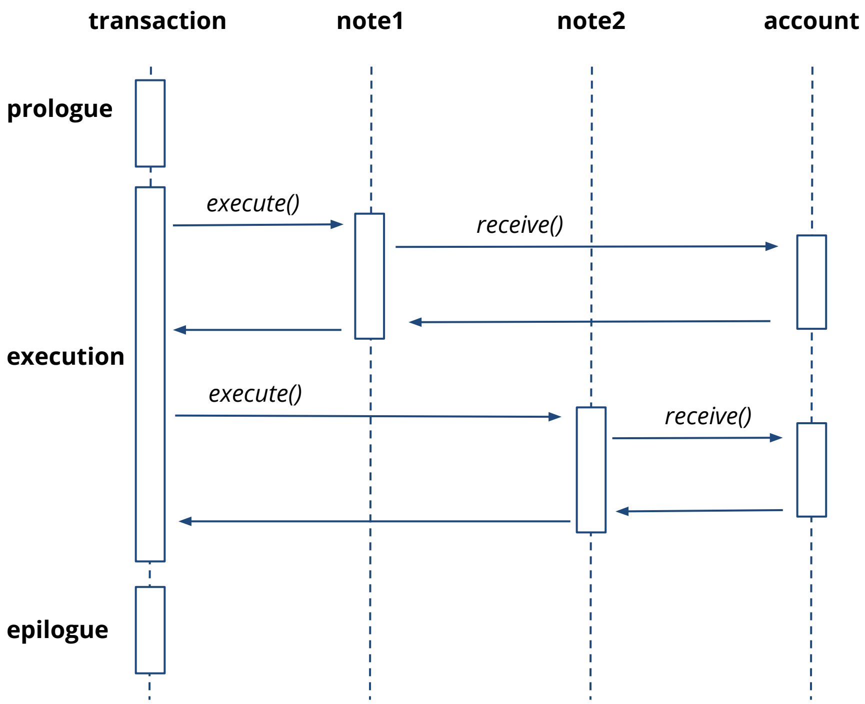
- Accounts maintain state and expose interface methods (Miden VM programs)
- Notes carry assets and specify a “spend script” (Miden VM program)
- Two transactions are needed to move assets between two accounts

Anatomy of a transaction



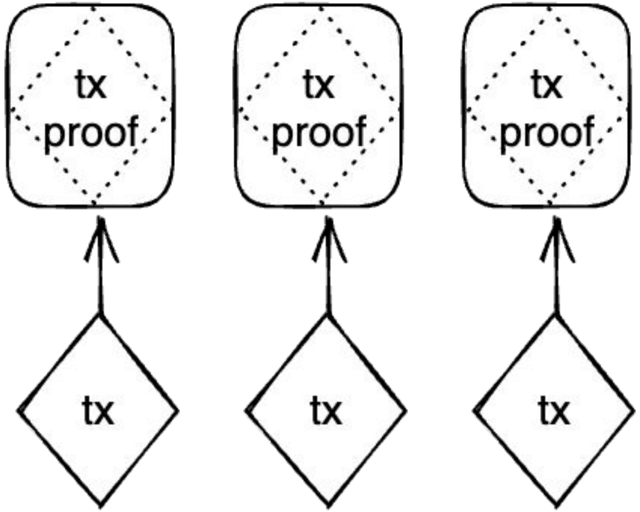
- Executed against a single account
- Consumes 0 or more notes
- Produces 0 or more notes

Executing transactions



- A note is consumed by executing its script
- Note script can call account's interface methods
- Account methods can modify account's state and create new notes
- Note scripts are executed sequentially one after another

Proving transactions

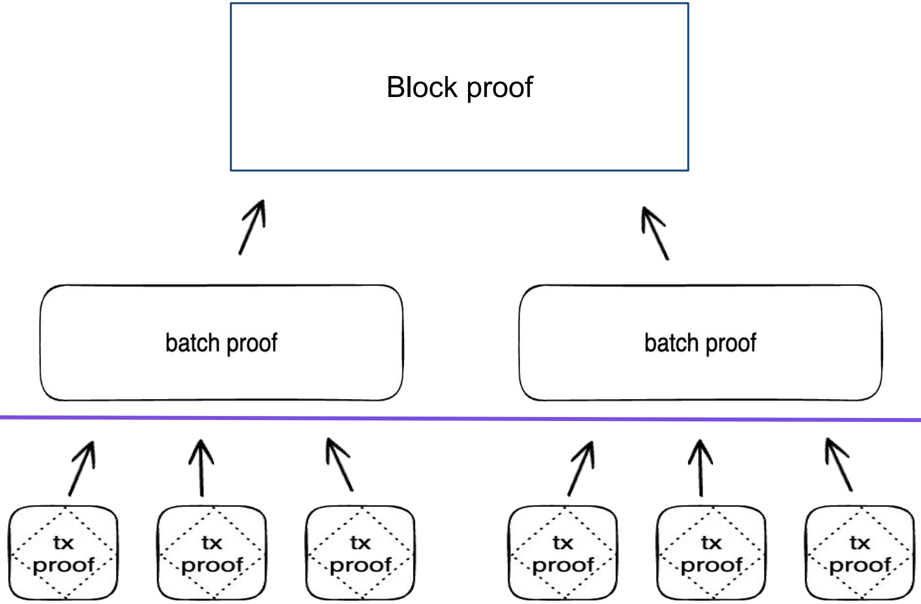


- Correctness of tx execution is proven with a STARK proof
- STARK proofs for all transactions are generated in parallel

Building a block proof

Must be done by network
(e.g., by the block producer)

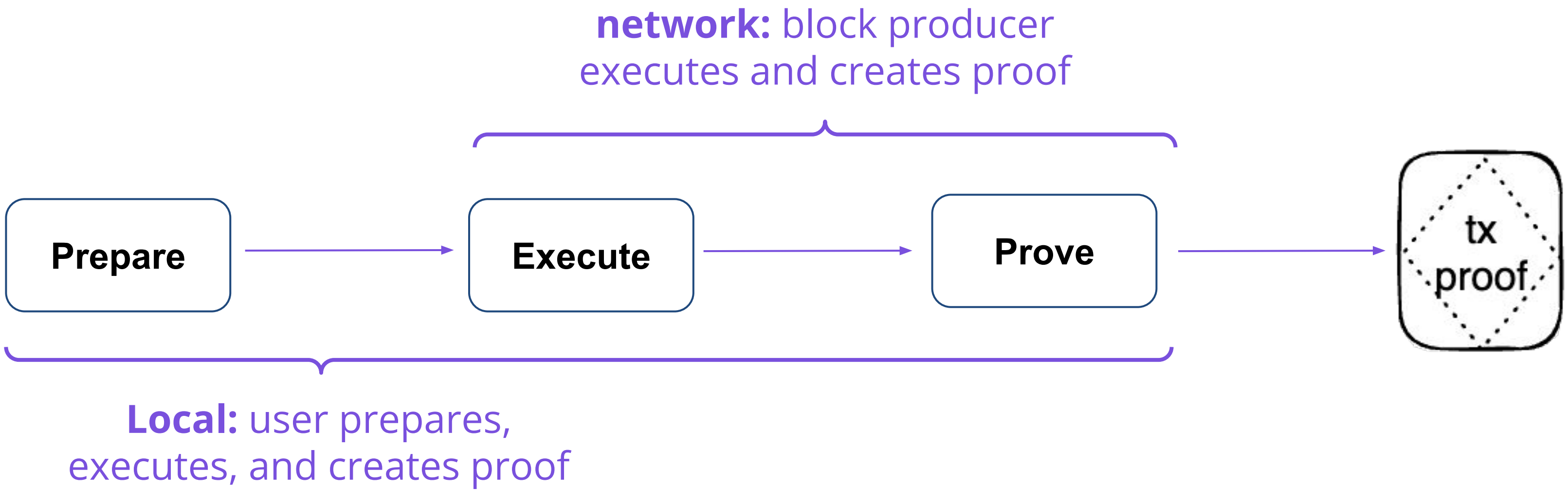
Recursive proof aggregation



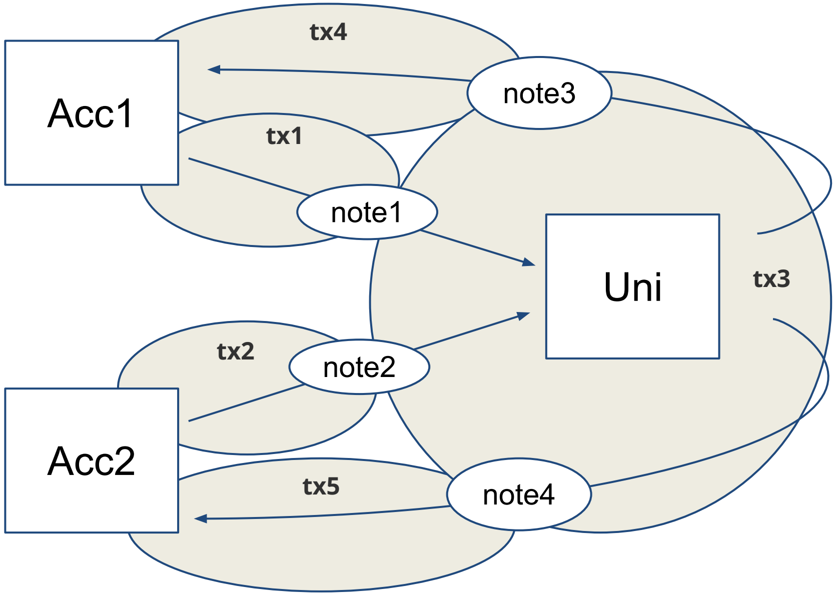
Can be done locally

Recursive proof aggregation

Local vs. network transactions



Handling shared state



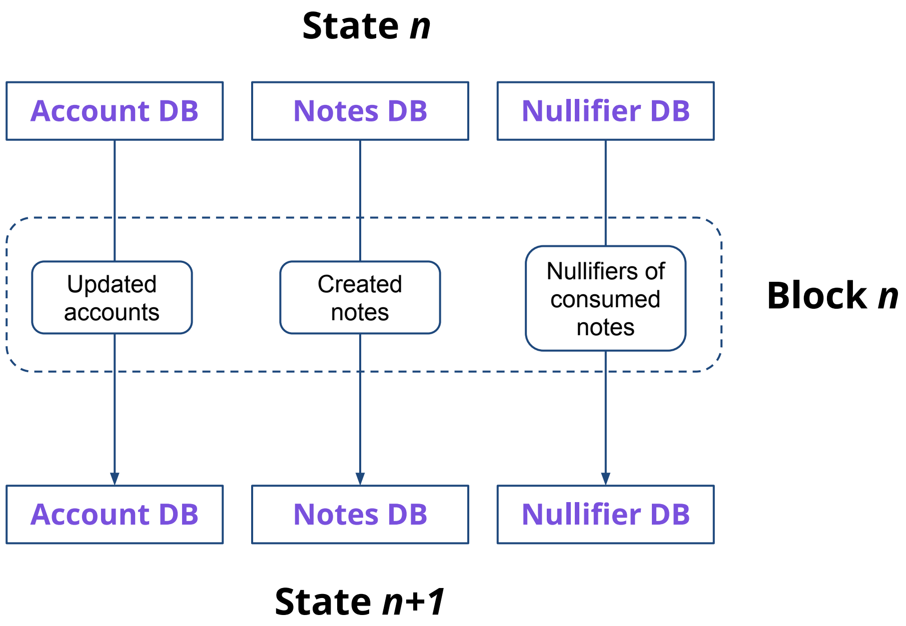
- Two users independently execute **tx1** and **tx2** which create notes 1 and 2
- Block producer creates and executes **tx3** which consumes notes 1 & 2 and outputs notes 3 and 4
- Two users independently execute **tx4** and **tx5** which consume notes 4 an 5

Transaction mode comparison

	Local execution	Network execution
Can be used with shared state	No	Yes
Can be private	Yes	No
Client hardware requirements	High	Low
Fees	Low	Higher

state model

Miden rollup state



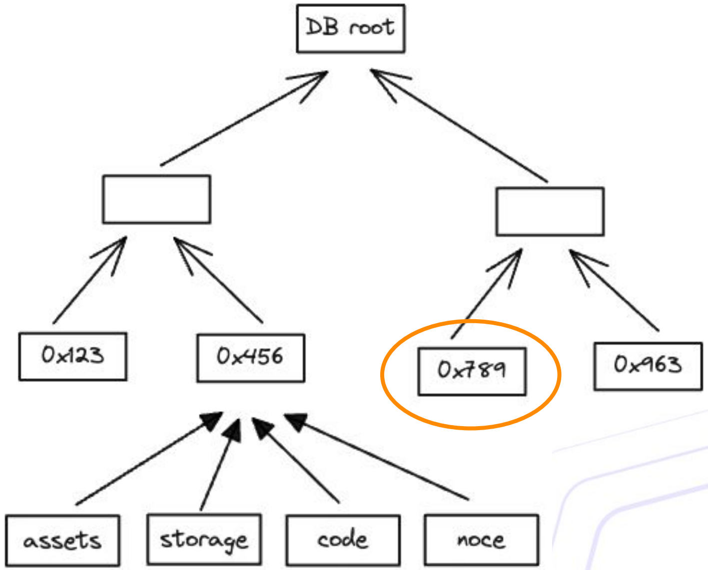
Account DB

Account DB stores **current state of all accounts**

For accounts with **on-chain state**, the entire state is stored by the nodes

For accounts with **off-chain state**, only the account hash is stored by the nodes

Sparse Merkle tree
(account id → account hash)



Notes DB

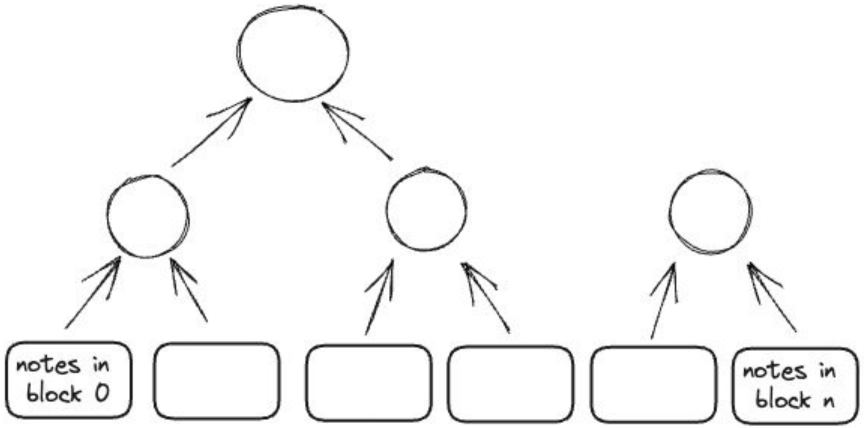
Notes DB stores **all notes ever created**

Notes can be added to the MMR even if **most nodes are discarded**

Inclusion witnesses never become stale, but they may need to be extended

Merkle Mountain Range

(append-only accumulator)



Nullifier DB

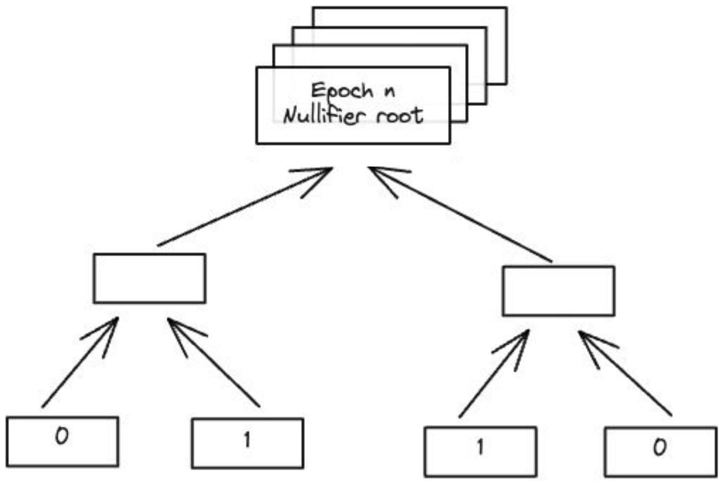
Nullifier DB keeps track of **all consumed notes**

Nullifiers are **organized into epochs** - e.g., 4 - 6 months

Nodes are expected to keep nullifiers for **last 2 epochs**

Sparse Merkle tree

(note hash → 1/0)



Miden state growth drivers

Account DB	Notes DB	Nullifier DB
Primary: number of accounts with on-chain state	**Primary:** number of unconsumed public notes	**Primary:** throughput (TPS)
Secondary: number of accounts	**Secondary:** number unconsumed notes	**Secondary:** nullifier epoch length
Pruning: discard on-chain account data (but retain account hash)	**Pruning:** discard on-chain note data	**Pruning:** n/a

conclusion

Flexible transaction modes

	On-chain data	Off-chain data
Network execution	Public transactions	Stateless transactions
Local execution	Local transactions	Private transactions

Addressing execution bloat

No re-execution

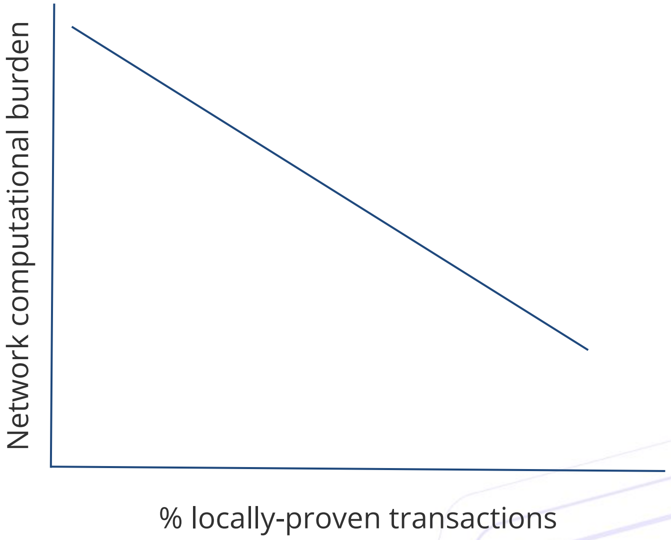
All transactions, including network transactions, are executed only once

Concurrent processing

Transactions can be processed concurrently by distinct network participants

Local execution

Transactions not affecting accounts with shared state can be executed and proven locally



Addressing state bloat

Dynamic pruning

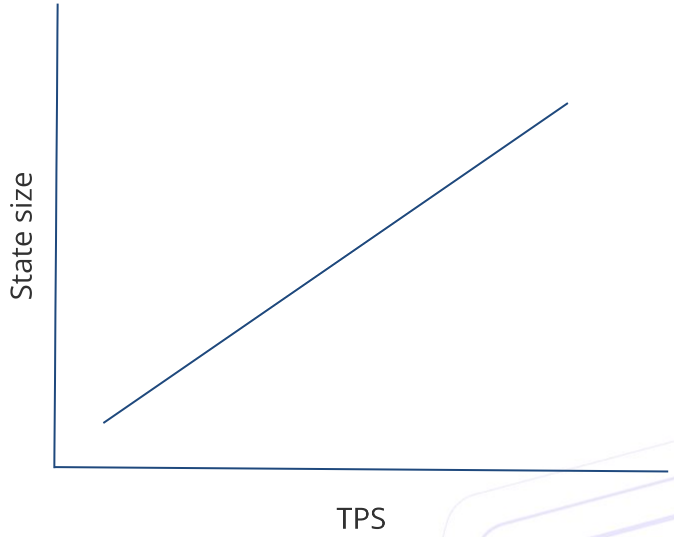
Block producers can independently decide which parts of the state to keep

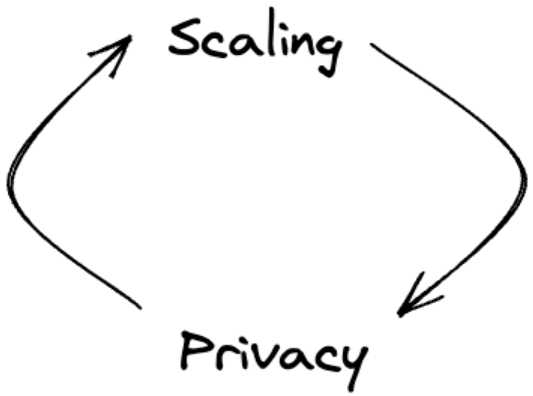
Light verifying nodes

Verifying nodes can discard vast majority of the state (i.e., the nullifier database)

State size driven by throughput

State size depends primarily on the current TPS rather than total number of accounts or notes




Scaling
Privacy

thanks

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Project lead, Polygon Miden

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