ETHEREUM 2.0 MASTERY PROGRAM

Instructor: Raja Rizwan Saleem

MODULE (3-5)

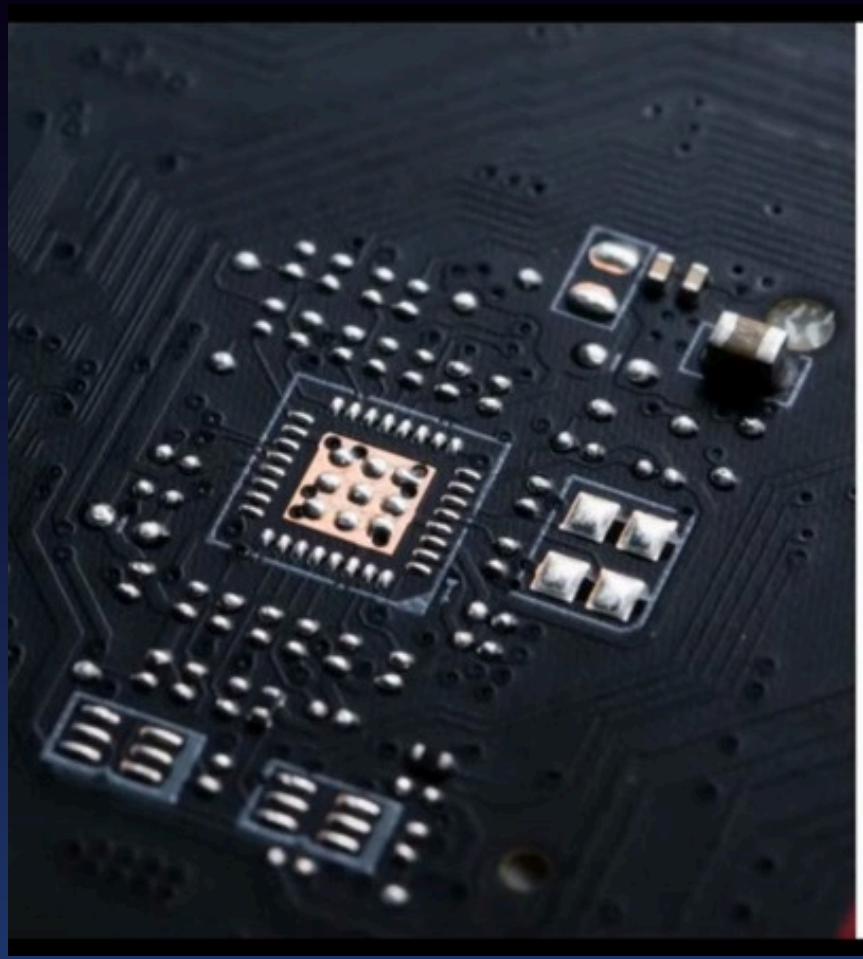
ETH 2.0 EXPLAINER

ETH 2.0 PHASES

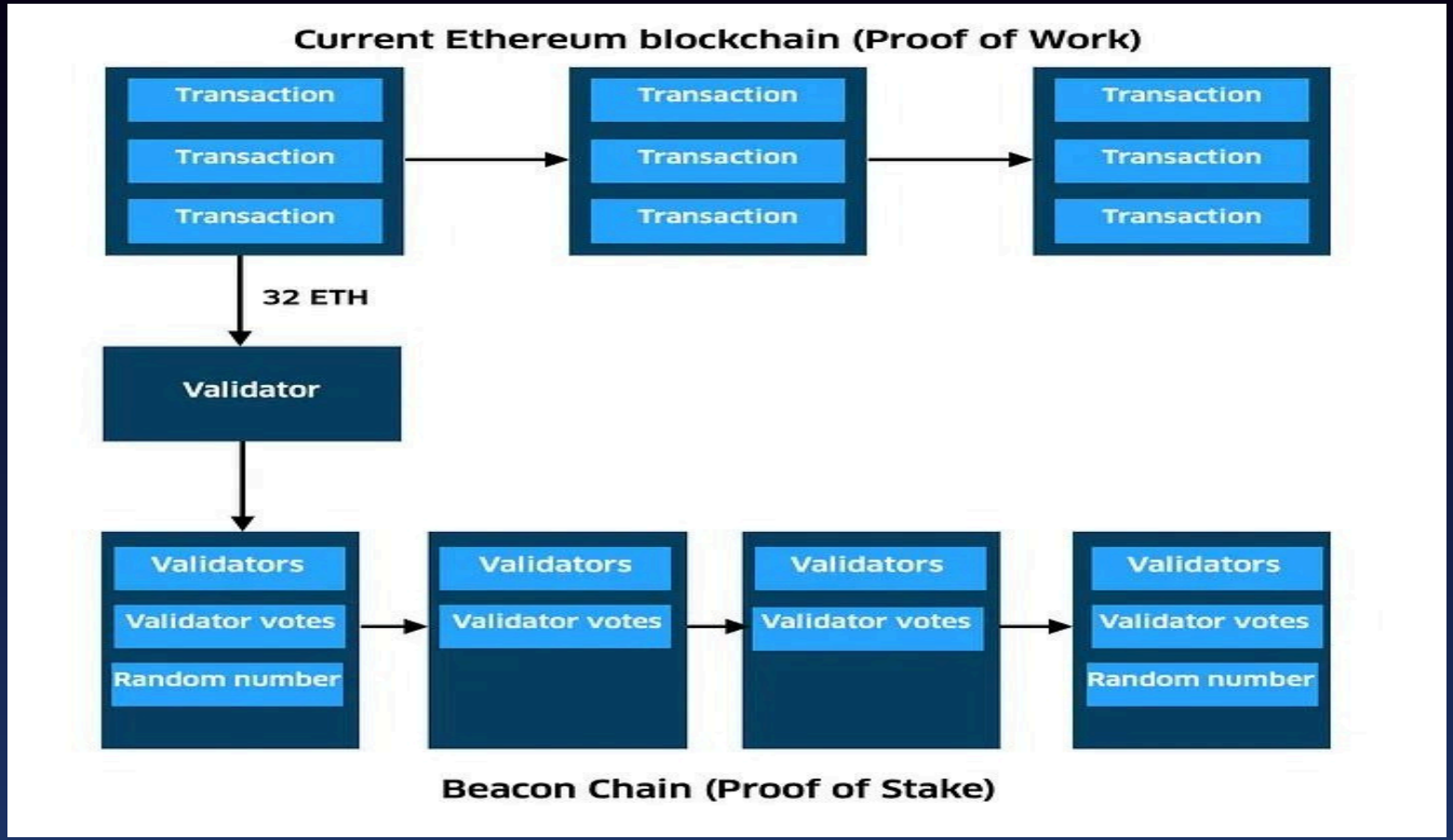
PROOF OF STAKE

Raja Rizwan Saleem
Lead Blockchain Trainer

Class-2



Sharding


Current Ethereum blockchain (Proof of Work)
Transaction
Transaction
Transaction
Transaction
Transaction
Transaction
Transaction
Transaction
Transaction
32 ETH
Validator
Validators
Validator votes
Random number
Validators
Validator votes
Validators
Validator votes
Validators
Validator votes
Random number
Beacon Chain (Proof of Stake)

Sharding

What is Sharding in Ethereum 2.0?

Sharding is a scalability solution for Ethereum 2.0 that aims to split the blockchain into multiple smaller chains (called shards) to handle more transactions in parallel — making the entire network faster and more efficient.

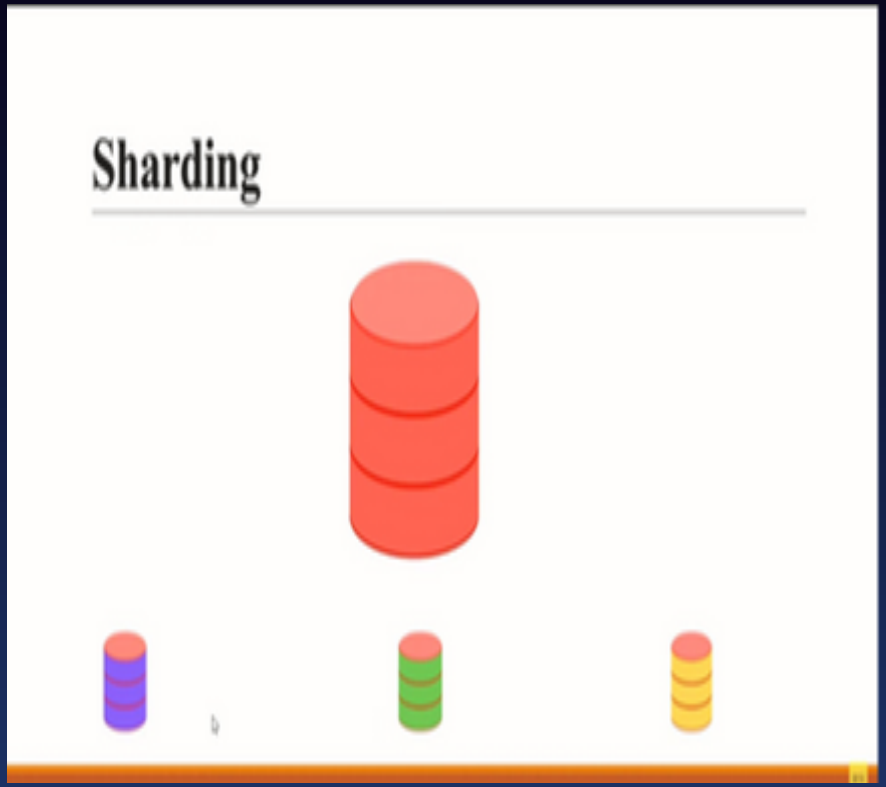
Sharding

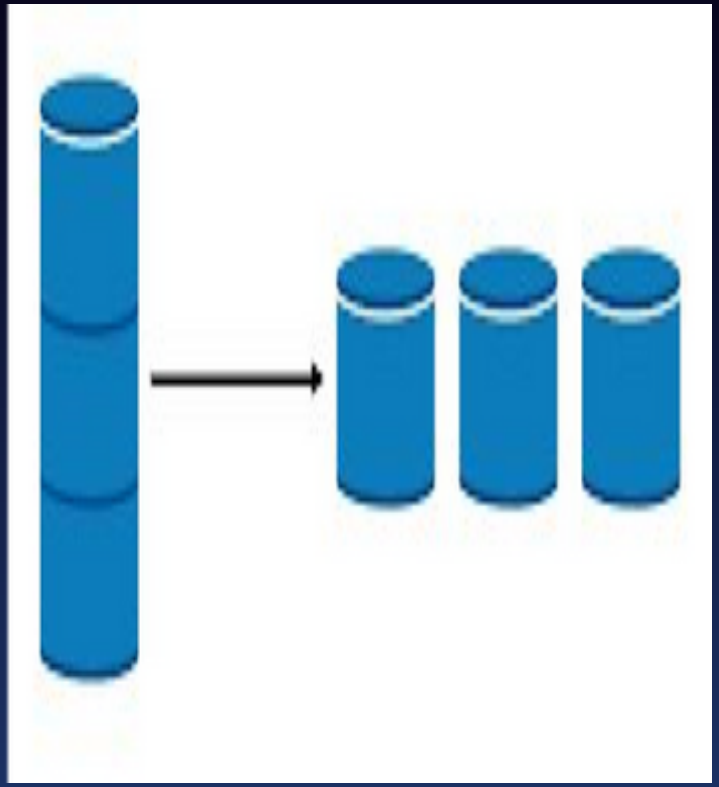
Simple Explanation

Think of Ethereum as a single-lane highway (current structure). All cars (transactions) must travel through this one lane, causing traffic jams (network congestion and high gas fees).
Sharding will turn Ethereum into a multi-lane highway, where traffic (data and transactions) is spread across many lanes (shards) — drastically improving throughput.

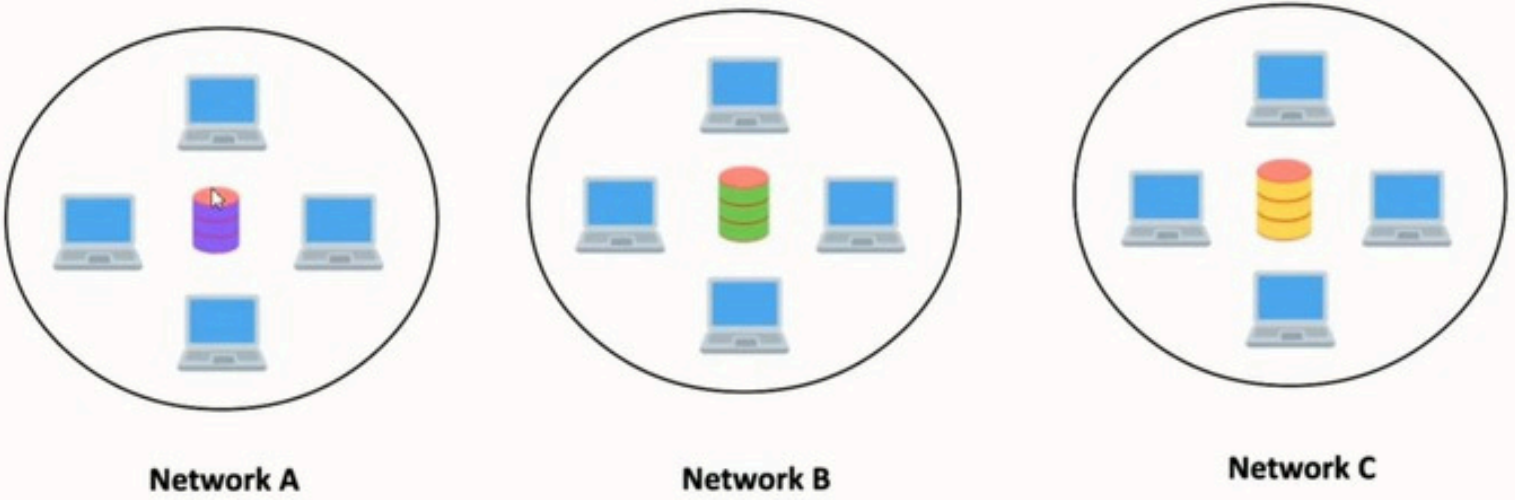
🔩 How Sharding Works in Ethereum 2.0

- 🔷 Ethereum will be split into **64 shards** (initially).
- 🔷 Each shard will **process its own transactions and smart contracts**.
- 🔷 All shards are **connected and coordinated by the Beacon Chain**.
- 🔷 **Validators are randomly assigned** to shards to ensure decentralization and prevent manipulation.


Sharding

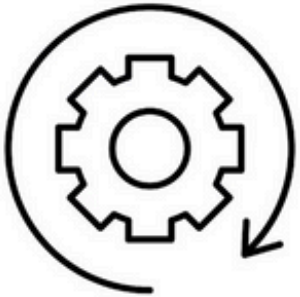


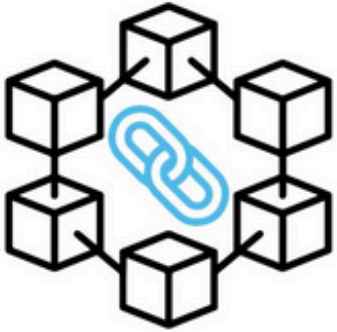
Sharding



Sharding

splitting a blockchain into multiple pieces,
or shards, and storing them in different places





Using sharding, its possible for nodes to function
without having to maintain all of that data at once

How Sharding is Done

Proof of stake (or PoS)

nodes validate transactions based on
the amount of tokens they have staked

stakers dealing with different shards
of the same blockchain, and accordingly
processing a network transaction

Proof of Work (or PoW)

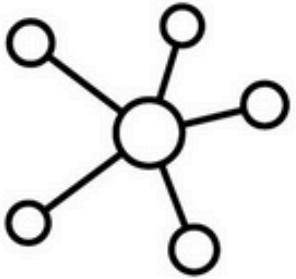
because network nodes face difficulty validating transactions with only the information from a single shard, and not the whole network

Full Node

archive a copy of the blockchains entire history on itself

SHARDING

full nodes no longer have to store or process the entirety of the networks activities



Sharding A-Big Picture

1. Shard Creation: In a sharded blockchain network, a central chain, often referred to as the **"Beacon Chain,"** manages and coordinates the operation of the shards. The Beacon Chain ensures that shards are synchronized, validators are assigned to shards, and consensus is maintained across the network.

2. Shards' Independence: Each shard operates like a mini-blockchain, containing its own subset of validators and transactions. Shards can process transactions and execute smart contracts without needing consensus from the entire network, which significantly improves scalability.

Sharding A-Big Picture

3. Parallel Processing: Shards work in parallel, enabling multiple transactions and smart contracts to be processed simultaneously across different shards. This parallel processing capability boosts the overall throughput of the blockchain network.

4. Cross-Shard Communication: Although shards operate independently, there's still a need for communication and coordination among them. Cross-shard communication mechanisms allow transactions that involve multiple shards to be processed smoothly. This is essential for maintaining consistency and integrity.

Sharding Benefits

- **Scalability:** Sharding greatly increases the network's transaction processing capacity, making it more suitable for mainstream adoption and high-demand applications.
- **Reduced Latency:** With transactions distributed across multiple shards, the overall network can process transactions more quickly, reducing latency.

- **Lower Fees:** Increased throughput and reduced congestion can lead to lower transaction fees, enhancing the user experience.
- **Energy Efficiency:** By processing fewer transactions per shard compared to a single-chain architecture, sharding can reduce energy consumption.

Major benfits

- Transactions per second increase.
- Powerful and expensive computers will not be needed.
- More validators will join.
- Energy consumption will reduce.

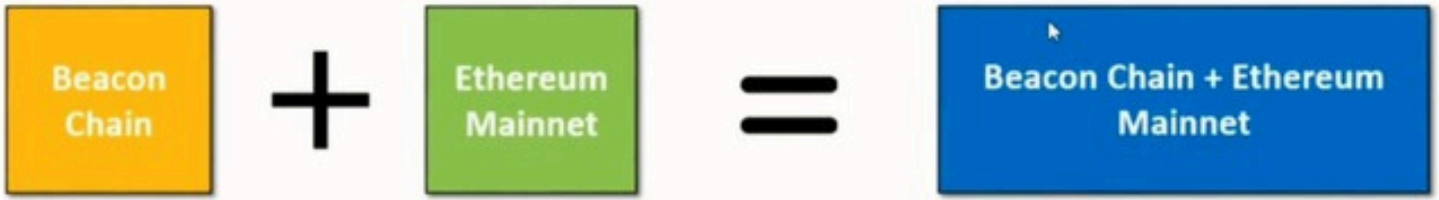
🎯 Key Benefits of Sharding

Benefit	Explanation
Scalability	More transactions can be processed in parallel.
Speed	Reduces congestion and improves transaction speed.
Lower Gas Fees	Easier handling of network load reduces transaction costs.
Decentralization	Validators can participate with lower hardware requirements.
Data Availability	Makes storing and accessing blockchain data more efficient.

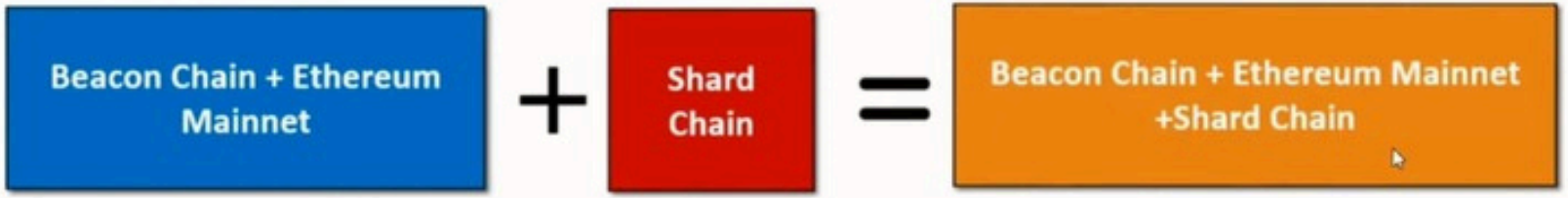
Sharding Challenges

- Ensuring secure cross-shard communication
- Managing data availability across shards.
- Maintaining overall network security.

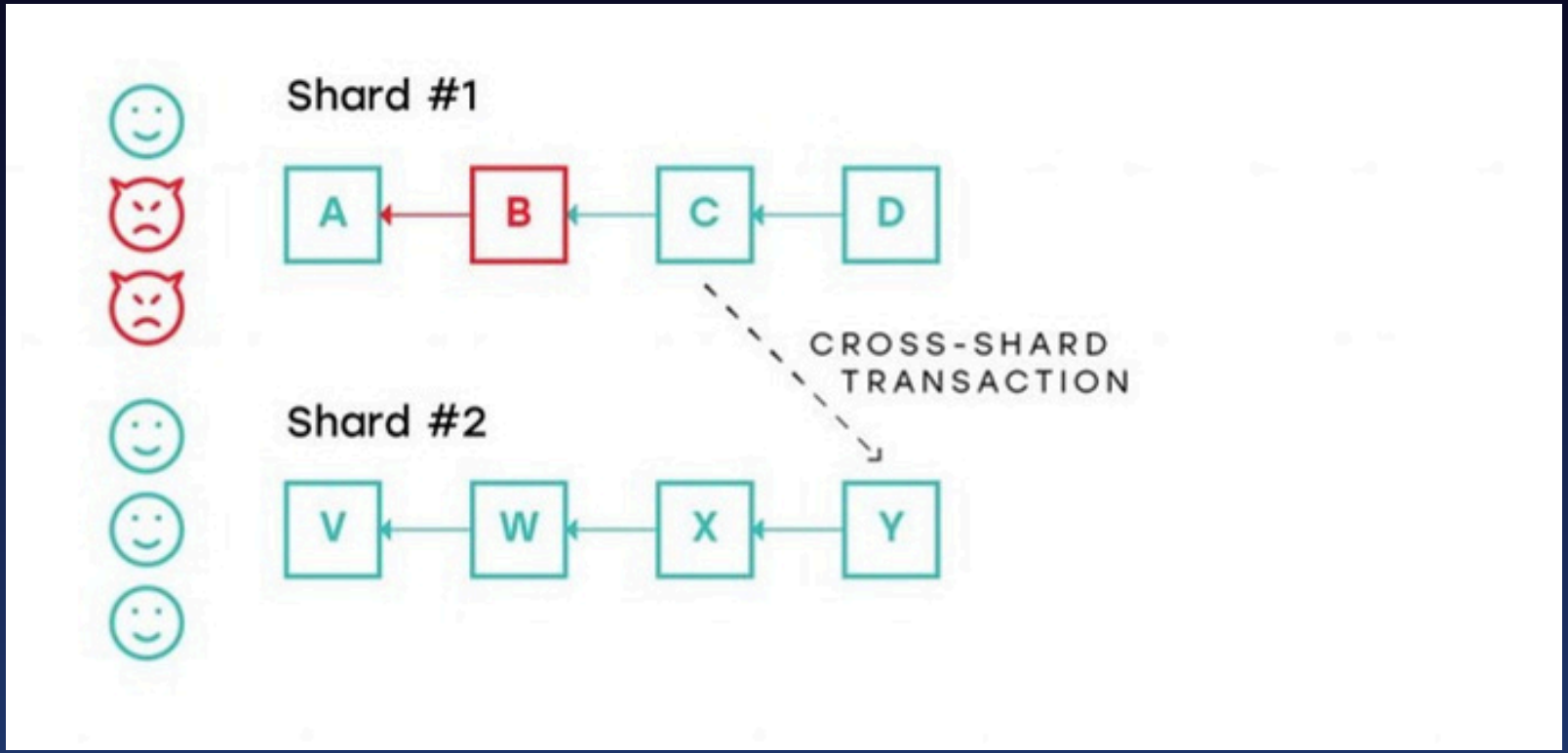
Sharding


Beacon Chain
+
Ethereum Mainnet
=
Beacon Chain + Ethereum Mainnet

Sharding


Beacon Chain + Ethereum Mainnet
+
Shard Chain
=
Beacon Chain + Ethereum Mainnet +Shard Chain

Cross-shard communication



Transaction Execution in POS

HOW A TRANSACTION GETS EXECUTED IN ETHEREUM POS

1. A user creates and signs a transaction with their private key. This is usually handled by a wallet or a library such as ether.js, web3js, web3py etc but under the hood the user is making a request to a node using the Ethereum JSON-RPC API. The user defines the amount of gas that they are prepared to pay as a tip to a validator to encourage them to include the transaction in a block. The tips get paid to the validator while the base fee gets burned.
2. The transaction is submitted to an Ethereum execution client which verifies its validity. This means ensuring that the sender has enough ETH to fulfill the transaction and they have signed it with the correct key.
3. If the transaction is valid, the execution client adds it to its local mempool (list of pending transactions) and also broadcasts it to other nodes over the execution layer gossip network. When other nodes hear about the transaction they add it to their local mempool too. Advanced users might refrain from broadcasting their transaction and instead forward it to specialized block builders such as Flashbots Auction. This allows them to organize the transactions in upcoming blocks for maximum profit (MEV).

HOW A TRANSACTION GETS EXECUTED IN ETHEREUM POS

4. One of the nodes on the network is the block proposer for the current slot, having previously been selected pseudo-randomly using RANDAO. This node is responsible for building and broadcasting the next block to be added to the Ethereum blockchain and updating the global state. The node is made up of three parts: an execution client, a consensus client and a validator client. The execution client bundles transactions from the local mempool into an "execution payload" and executes them locally to generate a state change. This information is passed to the consensus client where the execution payload is wrapped as part of a "beacon block" that also contains information about rewards, penalties, slashings, attestations etc. that enable the network to agree on the sequence of blocks at the head of the chain

HOW A TRANSACTION GETS EXECUTED IN ETHEREUM POS

5. Other nodes receive the new beacon block on the consensus layer gossip network. They pass it to their execution client where the transactions are re-executed locally to ensure the proposed state change is valid. The validator client then attests that the block is valid and is the logical next block in their view of the chain (meaning it builds on the chain with the greatest weight of attestations as defined in the fork choice rules). The block is added to the local database in each node that attests to it.

6. The transaction can be considered "finalized" if it has become part of a chain with a "supermajority link" between two checkpoints. Checkpoints occur at the start of each epoch and they exist to account for the fact that only a subset of active validators attest in each slot, but all active validators attest across each epoch. Therefore, it is only between epochs that a 'supermajority link' can be demonstrated (this is where 66% of the total staked ETH on the network agrees on two checkpoints).

Ethereum 2.O Phases

Ethereum 2.0 Phases

Ethereum 2.0 has three phases:

Phase 0 – Beacon Chain
Phase 1 – shards
Phase 2 – execution

An analogy with the human body:

Phase 0 – heart
Phase 1 – limbs
Phase 2 – brain

An analogy with an orchestra that's tough to beat:

Phase 0 – conductor
Phase 1 – instruments
Phase 2 – musicians

Ethereum 2.0 Phases

All phases are integral to the system and have different characteristics.

- Phase 0 is part of Ethereum 2020.
- Phase 1 is generally more inanimate and static than the other phases.
- Phase 2 is generally about action and agency.

Ethereum 2.0 Phases

Phase 0: Beacon Chain (PoS Implementation) The Beacon Chain is the foundational component of Ethereum 2.0. It operates as a separate PoS blockchain that introduces validators and staking. The main goals of Phase 0 are to establish the PoS system and prepare for the subsequent phases. Key features of Phase 0 include:

- Launch of the Beacon Chain.
- Introduction of validator nodes that participate in consensus by proposing and attesting to blocks.
- Validators stake Ether as collateral to participate and secure the network.
- Beacon Chain manages the PoS consensus and coordination of shard chains.

Purpose of the Beacon Chain

- Store information about validators and their stakes, ensuring each validator has at least 32 ETH staked
- Select block proposers for each shard in every slot
- Organize validators into committees to vote on the validity of proposed blocks
- Distribute rewards and impose penalties on validators
- Monitor the behavior of validators to ensure compliance
- Reward validators for following the rules
- Penalize malicious behavior, such as:
- Voting on two chains simultaneously (slashing)
- In severe cases, remove validators from the system entirely
- Establish mechanisms for determining finality
- Enable crosslinks between shards:
- The current state of each shard is recorded in a Beacon Chain block as a cross link
- Once the Beacon Chain block is finalized, the shard block is also considered finalized
- Other shards can then rely on this for cross-shard transactions

Ethereum 2.0 Phases

Phase 1: Shard Chains (Data Sharding) Phase 1 focuses on introducing shard chains to Ethereum blockchain. Sharding involves dividing the Ethereum network into smaller chains (shards), each capable of processing its own transactions and smart contracts. However, in Phase 1, these shard chains primarily focus on data storage rather than full smart contract execution. Key features of Phase 1 include:

- Introduction of shard chains, each responsible for storing data.
- Shards work in parallel, enhancing the overall capacity to process transactions.
- Cross-links connect the Beacon Chain to shard chains, allowing data availability and secure communication.

Ethereum 2.0 Phases

Phase 1.5: Eth1-Eth2 Merger (PoS Mainnet) Phase 1.5 marks the transition from the current Ethereum PoW mainnet to the PoS-based Ethereum 2.0 network. This phase involves merging the existing Ethereum 1.0 mainnet into the Ethereum 2.0 framework. The PoW chain becomes one of the shard chains, while the Beacon Chain continues to manage PoS consensus. Key features of Phase 1.5 include:

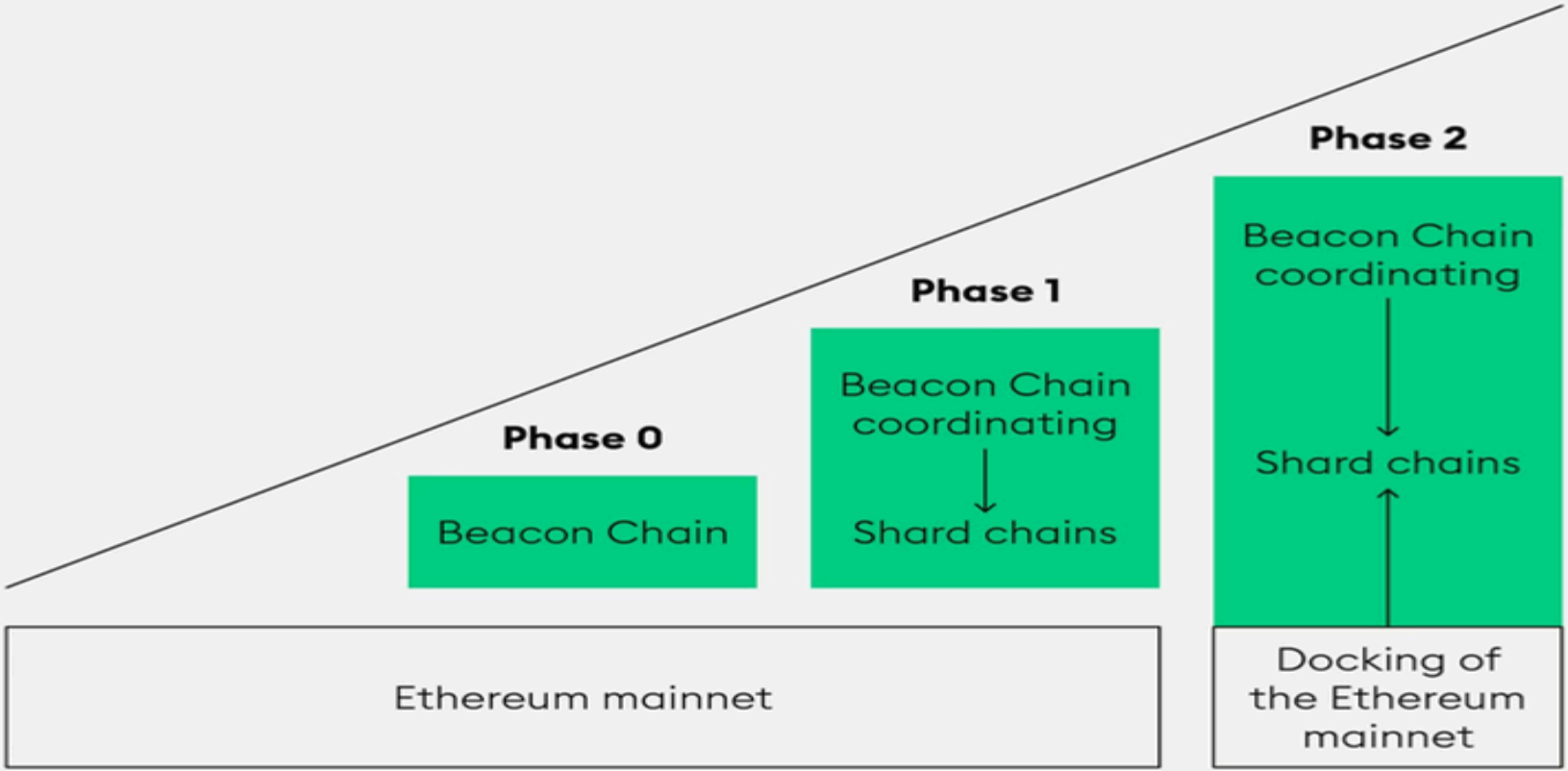
- Transition from PoW to PoS for the main Ethereum network.
- Eth1 chain becomes a shard within the Eth2 framework.
- Validators secure the network, and PoS is fully operational.

Ethereum 2.0 Phases

Phase 2: Full Sharding and Execution Environments Phase 2 is the most extensive and ambitious phase of Ethereum 2.0. It aims to complete the transition to full sharding and implement execution environments on shard chains. In this phase, shard chains become capable of executing smart contracts and transactions more akin to the current Ethereum mainnet. Key features of Phase 2 include:

- Full execution environments on shard chains, enabling smart contract execution.
- Cross-shard communication and coordination mechanisms.
- Enhanced scalability, efficiency, and throughput.

It's important to note that these phases represent a general roadmap for Ethereum 2.0. The actual development and deployment process might involve adjustments, optimizations, and improvements based on research, community feedback, and technical considerations. The Ethereum community and developers work collaboratively to achieve the goals set out in these phases.


Phase 2
Beacon Chain coordinating
Shard chains
Phase 1
Beacon Chain coordinating
Shard chains
Phase 0
Beacon Chain
Ethereum mainnet
Docking of the Ethereum mainnet

Ethereum 2.0 (a.k.a. Ethereum's Consensus Layer Upgrade)

Ethereum 2.0 is not a new blockchain, but an upgrade to improve scalability, security, and sustainability by transitioning from Proof of Work (PoW) to Proof of Stake (PoS), and beyond.

Ethereum 2.0 (a.k.a. Ethereum's Consensus Layer Upgrade)

✅ Phase 0 – Beacon Chain (Live)

- 📅 **Launched:** December 1, 2020
- 🧠 **What it did:**
  - Introduced **Proof of Stake (PoS)**.
  - Operated **separately** from Ethereum Mainnet.
  - Allowed users to **stake ETH (32 ETH minimum)**.
- ❌ No smart contracts or dApps — just a coordination chain.

Ethereum 2.0 (a.k.a. Ethereum's Consensus Layer Upgrade)

✅ Phase 1 – The Merge (Completed)

- 📅 **Completed:** September 15, 2022
- 🔄 **What happened:**
  - Ethereum Mainnet merged with the Beacon Chain.
  - Ethereum **completely transitioned to PoS**.
  - **Mining was eliminated** — validators now secure the network.
  - Cut energy use by **~99.95%**.

Ethereum 2.0 (a.k.a. Ethereum's Consensus Layer Upgrade)

🛠️ Phase 2 (and Beyond) – Scalability & Enhancements

This phase is ongoing and divided into multiple sub-phases for optimization:

🧩 The Surge *(Scalability)*

- 🌐 Introduces **sharding** (splitting the blockchain into multiple parts for parallel processing).
- 🔗 Combined with **Layer 2 rollups** for massive transaction throughput (100,000+ TPS goal).
- 🧠 **Goal:** Make Ethereum highly scalable and cost-efficient.

🧱 The Verge *(Data Efficiency)*

- 🧬 Introduces **Verkle Trees** (advanced data structure).
- 🧠 Goal: Reduce validator hardware requirements.
- Makes Ethereum more **decentralized and accessible**.

Ethereum 2.0 (a.k.a. Ethereum's Consensus Layer Upgrade)

🛠️ Phase 2 (and Beyond) – Scalability & Enhancements

This phase is ongoing and divided into multiple sub-phases for optimization:

🧹 The Purge *(Node Simplification)*

- 🗑️ Removes unnecessary old data.
- 🧠 Goal: **Reduce storage burden** for validators.
- Supports **long-term sustainability**.

🎯 The Splurge *(Miscellaneous Improvements)*

- 🎉 Final clean-up phase for smaller enhancements.
- Ensures all upgrades work smoothly together.

Ethereum 2.0 (a.k.a. Ethereum's Consensus Layer Upgrade)

✅ Quick Summary Table

Phase	Status	Key Purpose
Beacon Chain	✅ Live	PoS chain launch
The Merge	✅ Complete	Transition to PoS (no more mining)
The Surge	🚧 Ongoing	Scalability (sharding, rollups)
The Scourge	🔜 Planned	Censorship resistance & MEV neutrality
The Verge	🔜 Planned	Efficient data storage (Verkle Trees)
The Purge	🔜 Planned	Simplify protocol, reduce node load
The Splurge	🔜 Planned	Final clean-up and fine-tuning

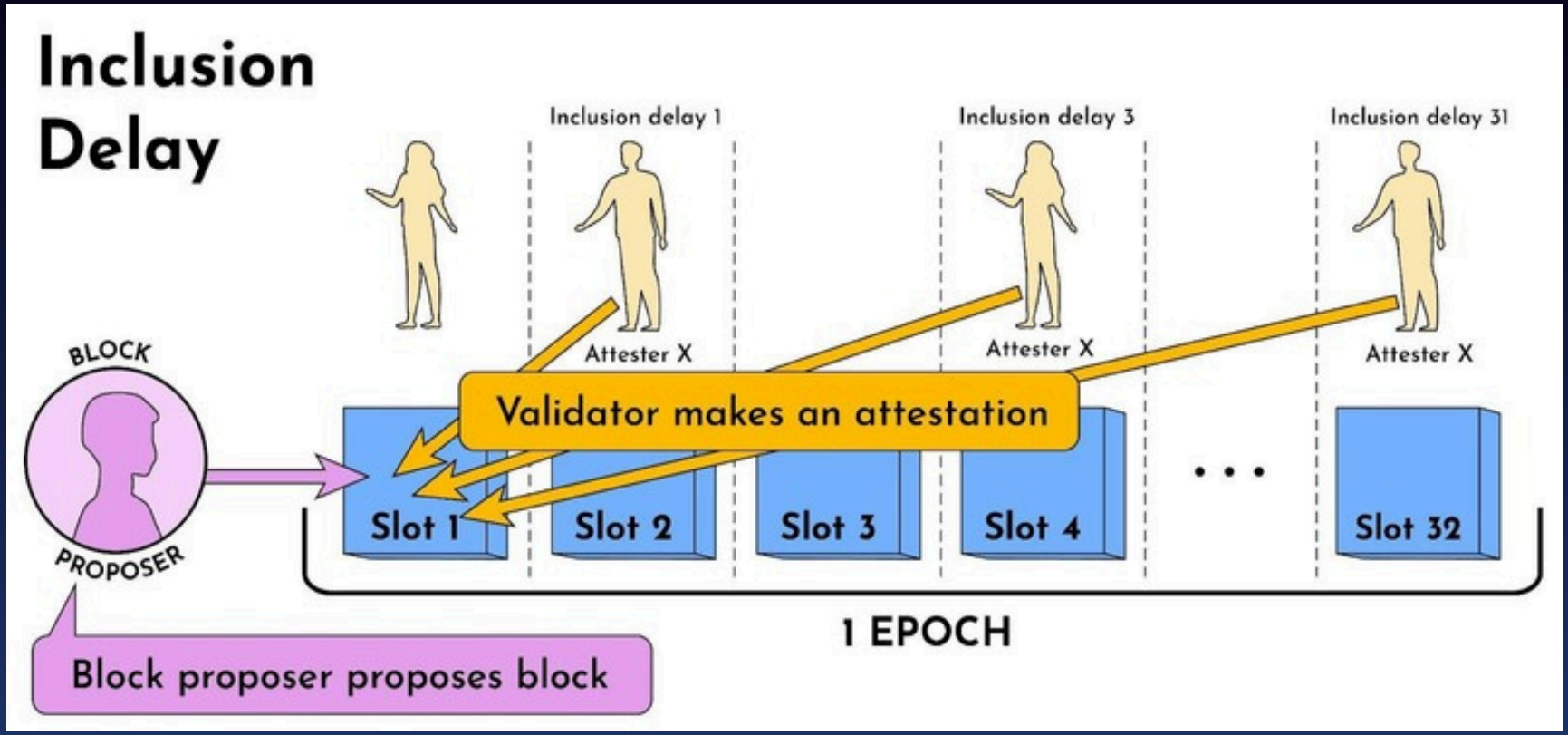
Slot & Epoch

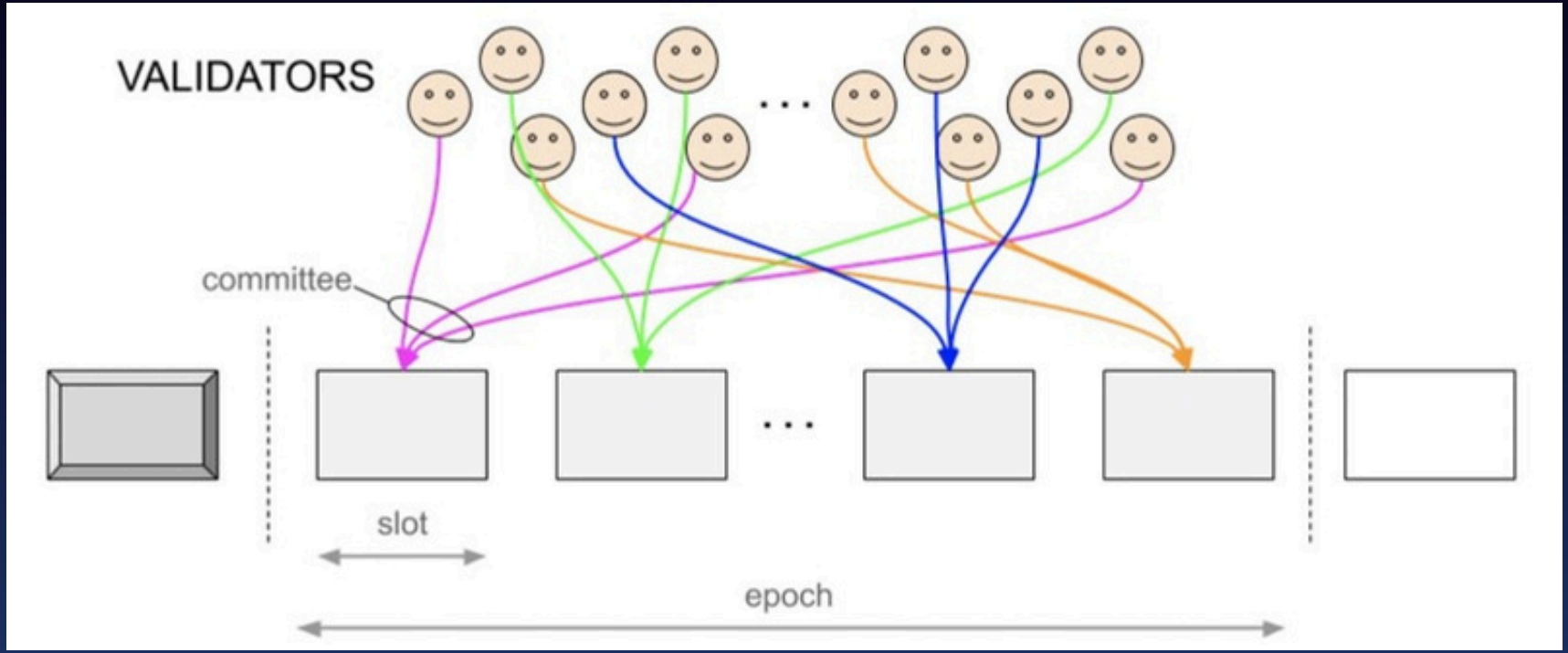
In the context of Ethereum 2.0 and its Proof of Stake (PoS) consensus mechanism, "slots" and "epochs" are important concepts that relate to the operation and organization of the network.

Slots

- 32 slots = 1 epoch
- Each slot lasts 12 seconds, during which a randomly chosen validator can propose a block
- Each slot may or may not contain a block
- Validators are split into committees, with one or more committees responsible for attesting to each slot
- Each committee consists of at least 128 validators
- One validator is selected as the aggregator for the slot
- The remaining 127 validators attest to the proposed block
- After every epoch, validators are reshuffled and assigned to new committees

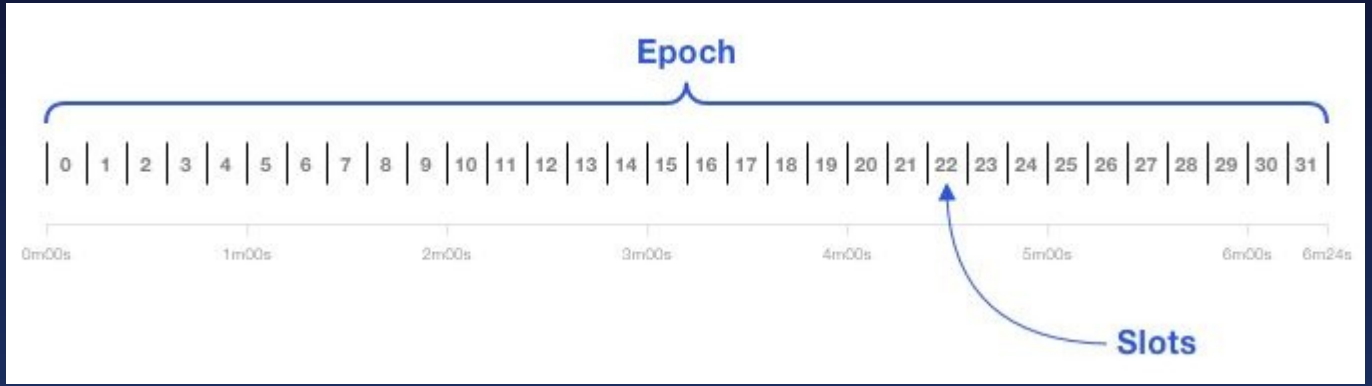
Slots


Inclusion Delay
Inclusion delay 1
Inclusion delay 3
Inclusion delay 31
Attester X
Attester X
Attester X
BLOCK
PROPOSER
Validator makes an attestation
Slot 1
Slot 2
Slot 3
Slot 4
Slot 32
1 EPOCH
Block proposer proposes block


VALIDATORS
committee
slot
epoch

Slot and Epochs

The Beacon Chain provides the heartbeat to Ethereum 2.0. It provides the tempo and rhythm for the system's harmony and consensus. Each slot is 12 seconds and an epoch is 32 slots: 6.4 minutes.



Slot and Epochs

A slot is a chance for a block to be added to the Beacon Chain and shards. You can imagine that the Beacon Chain and shard chains are choreographed in lockstep. Every 12 seconds, one beacon (chain) block and 64 shard blocks are added when the system is running optimally. Validators do need to be roughly synchronized with time.

A slot is like the block time, but slots can be empty. Genesis blocks for the Beacon Chain and shards are at Slot 0. Shards will start at a future epoch than the Beacon Chain's Epoch 0, but will have their own Epoch 0 that includes their genesis blocks.

Slot and Epochs

- Validators take turns proposing blocks in consecutive slots.
- A validator chance to propose a block is determined by their weight, which is influenced by the amount of Ether they have staked and other factors.
- Once a validator proposes a block in a slot, that block contains transactions and attestations from other validators, indicating agreement on the state of the network.
- If a validator misses their turn or behaves maliciously, they might lose a portion of their staked Ether as a penalty.

Epochs

Represents the number of 32 slots and takes approximately **6.4 minutes.** Epochs play an important role when it comes to the validator queue and finality.

An epoch is a larger unit of time in Ethereum 2.0, composed of a fixed number of slots. Each epoch consists of 32 slots. An epoch is approximately 6.4 minutes long (32 slots * 12 seconds per slot). The concept of epochs helps organize various activities and processes within the Ethereum 2.0 network. Some key aspects related to epochs include:

Epochs

- **Validator Rotation:** Validators are shuffled and reorganized at the beginning of each epoch. This process helps distribute the opportunity to participate in block proposing and attesting more fairly.
- **Reward Distribution:** Rewards and penalties for validators are calculated at the end of each epoch. This includes rewards for proposing blocks, attesting correctly, and penalties for misbehavior.
- **State Transitions:** Certain state transitions, such as updating the active validator set, occur at the boundary between epochs. This ensures smooth network operations.
- **Slashing:** Slashing refers to the penalty imposed on validators who behave maliciously or contradict the consensus rules. Slashing is applied based on evidence from multiple validators and can result in a loss of staked Ether.

Introduction to Validators, Attestations, and the Beacon Chain

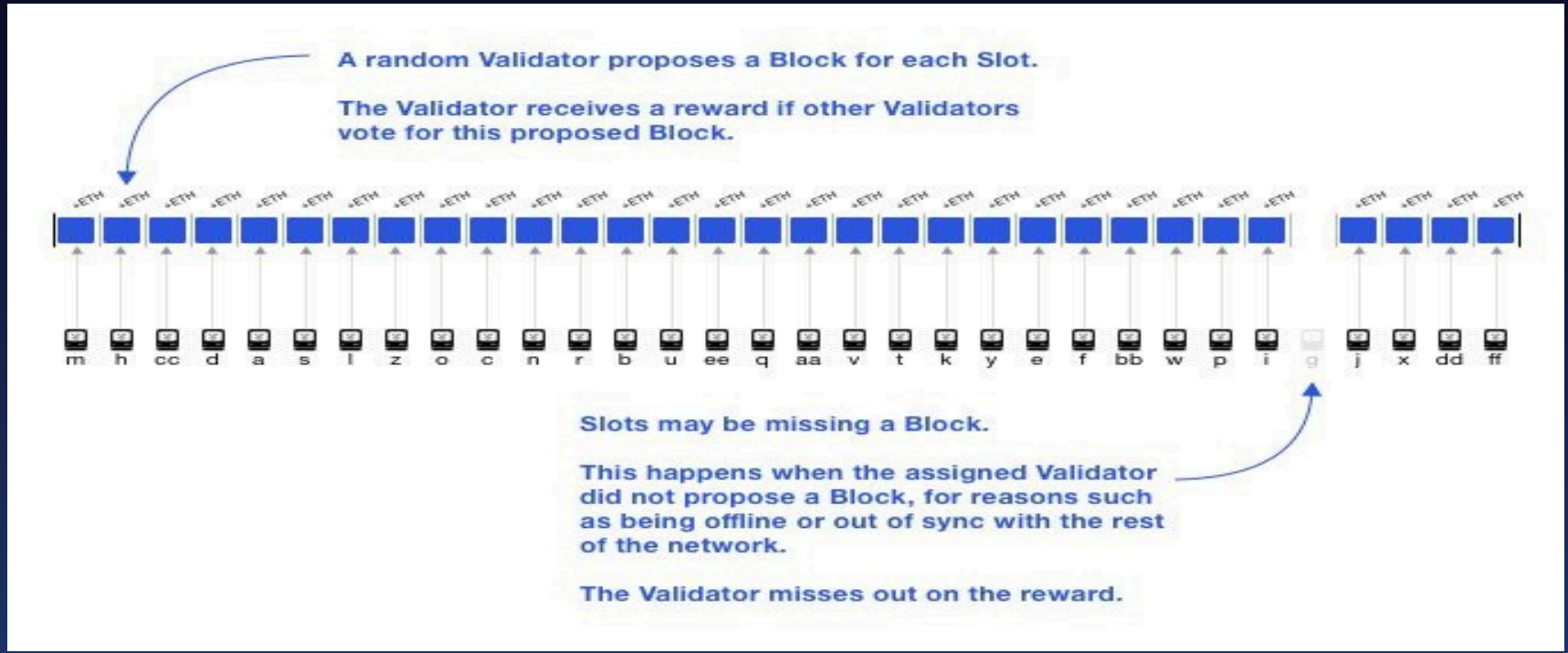
Introduction to Validators, Attestations and the Beacon Chain

While Proof of Work (PoW) is associated with miners, in Ethereum 2.0 validators are Proof of Stake “virtual miners”. Validators are actively participating in the consensus of the Ethereum 2.0 protocol.

A block proposer is a validator that has been pseudorandomly selected to build a block.

Most of the time, validators are attesters that vote on beacon blocks and shard blocks. These votes are recorded in the Beacon Chain. The votes determine the head of the Beacon Chain, and the heads of shards.

Introduction to Validators, Attestations and the Beacon Chain



Introduction to Validators, Attestations and the Beacon Chain

At every epoch, a validator is pseudorandomly assigned to a slot and shard. The validator is participating in the consensus of that assigned shard so that it can vote for that shard's head. The validator links the shard head to the beacon block for a slot.

An attestation is a validator's vote, weighted by the validator's balance. Attestations are broadcasted by validators in addition to blocks.

Validators also police each other and are rewarded for reporting other validators that make conflicting votes, or propose multiple blocks.

The contents of the Beacon Chain is primarily a registry of validator addresses, the state of each validator, attestations, and links to shards.

Introduction to Validators, Attestations and the Beacon Chain

Validators overview:

- Validators participate by staking Ether as collateral, showing their commitment to network security and integrity
- Block Proposing:
- Validators take turns proposing blocks during time slots
- Selection is influenced by the validator's stake and past performance
- Attesting:
- Validators attest to the validity of blocks proposed by others
- These attestations serve as votes affirming the block's validity and network state
- Rewards and Penalties:
- Validators earn rewards for correctly proposing and attesting to blocks
- Validators face penalties for malicious actions or rule violations
- Slashing:
- A strict penalty mechanism for severe misbehavior
- If proven guilty, a portion of the validator's staked Ether is slashed
- Evidence from other validators is required to trigger slashing

Introduction to Validators, Attestations and the Beacon Chain

- Attestations are a key component of Ethereum 2.0's Proof-of-Stake (PoS) consensus mechanism
- Serve as votes of agreement on the current state of the network and which block should be added to the blockchain
- Enhance network security by confirming block validity and ensuring consensus among validators
- Validators submit attestations to indicate agreement with a specific block and its transactions
- Attestations act as evidence of a block's validity
- Help create crosslinks between the Beacon Chain and shard chains
- Crosslinks confirm inclusion of shard data in the Beacon Chain, ensuring consistency across the network
- Proposing validators include attestations in the blocks they propose
- Inclusion of attestations increases the security and legitimacy of proposed blocks

Introduction to Validators, Attestations and the Beacon Chain

Validators need to deposit 32 ETH into the validator deposit contract on the Ethereum 1.0 chain. Validator operators have to run a validator node. Its job is to propose blocks and sign attestations. A validator has to be online for at least 50% of the time in order to have positive returns.

Validator

- To participate as a validator, a user must deposit 32 ETH into the deposit contract and run three separate pieces of software: an execution client, a consensus client, and a validator. On depositing their ETH, the user joins an activation queue that limits the rate of new validators joining the network. Once activated, validators receive new blocks from peers on the Ethereum network. The transactions delivered in the block are re-executed to check that the proposed changes to Ethereum's state are valid, and the block signature is checked. The validator then sends a vote (called an attestation) in favor of that block across the network.

Validator

- Whereas under proof-of-work, the timing of blocks is determined by the mining difficulty, in proof-of-stake, the tempo is fixed. Time in proof-of-stake Ethereum is divided into slots (12 seconds) and epochs (32 slots). One validator is randomly selected to be a block proposer in every slot. This validator is responsible for creating a new block and sending it out to other nodes on the network. Also in every slot, a committee of validators is randomly chosen, whose votes are used to determine the validity of the block being proposed. Dividing the validator set up into committees is important for keeping the network load manageable. Committees divide up the validator set so that every active validator attests in every epoch, but not in every slot.

Validators

Validator

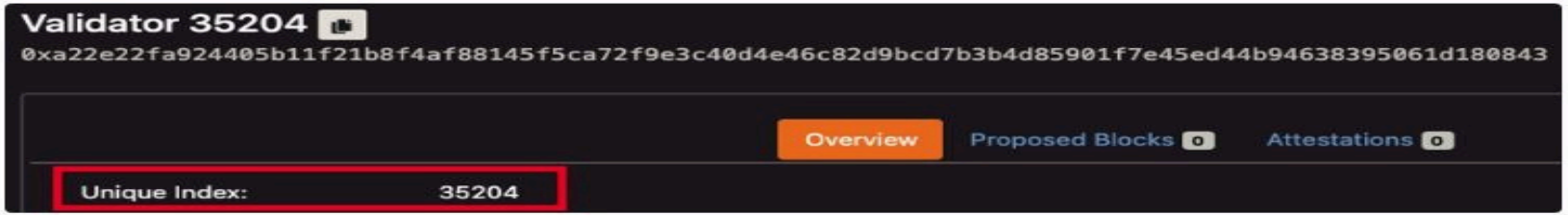
Validators need to deposit 32 ETH into the validator deposit contract on the Ethereum 1.0 chain.
Validator operators have to run a validator node. Its job is to propose blocks and sign attestations.
A validator has to be online for at least 50% of the time in order to have positive returns.

Eligible for activation & Estimated activation

Refers to pending validators. The deposit has been recognized by the ETH2 chain at the timestamp of "Eligible for activation". If there is a queue of pending validators, an estimated timestamp for activation is calculated.

Unique Index

Every validator receives its unique index. beaconcha.in.



THANK-YOU