# Lesson 17: Proof of Stake

## Module 2: Blockchain Fundamentals

Digital Finance

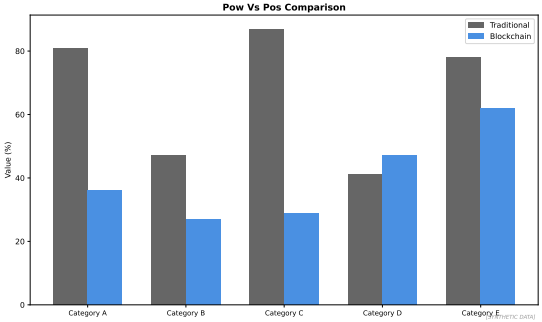
# Why Proof of Stake?

**Proof of Work Limitations:**

- Energy consumption (150+ TWh/year)
- Hardware waste (ASICs obsolete in 1–2 years)
- Centralization pressure (economies of scale)
- Slow finality (probabilistic)

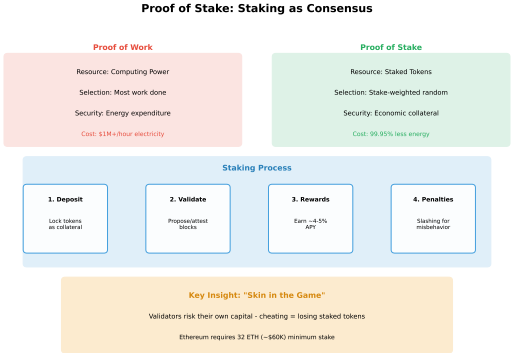
**PoS Alternative:**

- Replace computation with capital
- Energy efficiency (99.95% reduction)
- Economic security
- Faster finality




**Proof-of-Stake offers energy efficiency while maintaining decentralization.**

# Core Concept: Stake as Security Deposit




**Key Idea:**

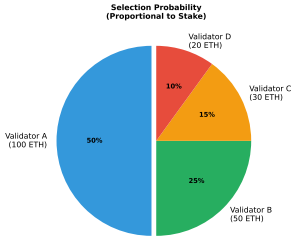
- Validators lock up capital (stake) as collateral
- Selected to propose blocks based on stake size
- Earn rewards for honest behavior
- Lose stake for dishonest behavior (slashing)
- **Attack cost:** Must acquire and lock majority of stake

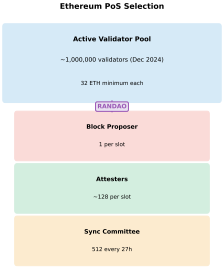
**Security analysis identifies vulnerabilities and helps design robust systems.**

# Validator Selection Mechanisms

1. **Random Selection (weighted):**
   - Higher stake = higher probability
   - Not purely proportional (prevents centralization)
   - Randomness from VRF (Verifiable Random Function)

2. **Coin Age:**
   - Priority based on stake × time held
   - Resets after block proposal
   - Incentivizes long-term holding




*Source: Ethereum Beacon Chain Specification, beaconcha.in (Dec 2024)*

**Key concepts from this slide inform practical applications in finance.**

# Ethereum's Proof of Stake: Beacon Chain

**Requirements:**

- Minimum stake: 32 ETH per validator
- Run validator node (beacon node + execution client)
- Uptime requirement: >99% to maintain profitability

**Epoch and Slot Structure:**

- **Slot:** 12 seconds (one block opportunity)
- **Epoch:** 32 slots = 6.4 minutes
- Each epoch, validators assigned to slots and committees
- Finality achieved after 2 epochs (∼13 minutes)

**Roles per Epoch:**

- **Proposer:** One validator per slot, proposes block
- **Attesters:** Committees of validators vote on block validity

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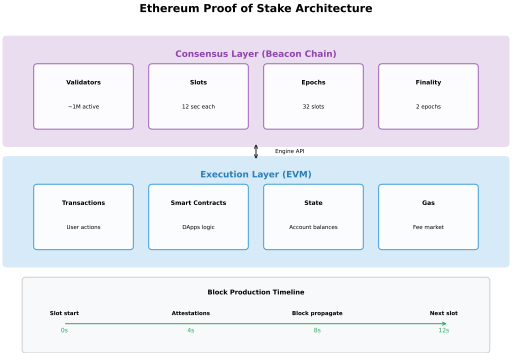
**Ethereum pioneered smart contracts and remains the dominant platform for DeFi and NFTs.**

# Ethereum PoS Architecture




*Source: Ethereum.org, The Merge Documentation (Sep 2022)*

**Consensus Flow:**

1. Proposer selected for slot (pseudo-random, stake-weighted)
2. Proposer creates block, broadcasts to network
3. Attesters vote on block (organized in committees)
4. Aggregated attestations included in next block
5. After 2 epochs, block finalized (cannot be reverted)

**Ethereum pioneered smart contracts and remains the dominant platform for DeFi and NFTs.**

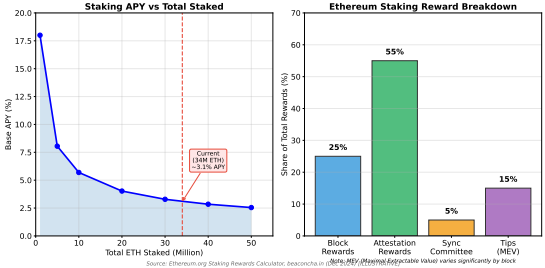
# Rewards and Penalties

**Rewards (per epoch):**

- Timely attestations: $\sim$0.000015 ETH
- Block proposals: $\sim$0.0002 ETH
- Sync committee: $\sim$0.0001 ETH
- Annual yield: 3–5% APR

**Penalties:**

- Offline: Miss rewards + small penalty
- Late attestations: Reduced rewards
- Slashing: Major stake loss (see next slide)

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# Slashing: Punishing Malicious Behavior

**Slashable Offenses:**

1. **Double Proposal:** Proposing two different blocks in same slot
2. **Surround Vote:** Attestation contradicting previous attestation
3. **Double Vote:** Two attestations for same slot with different targets

**Slashing Penalties:**

- Immediate penalty: 1 ETH (minimum)
- Correlation penalty: Scales with number of validators slashed simultaneously
- Maximum penalty: Entire 32 ETH stake (if many validators slashed together)
- Forced exit: Validator ejected from network

**Design Goal:** Make coordinated attacks extremely expensive

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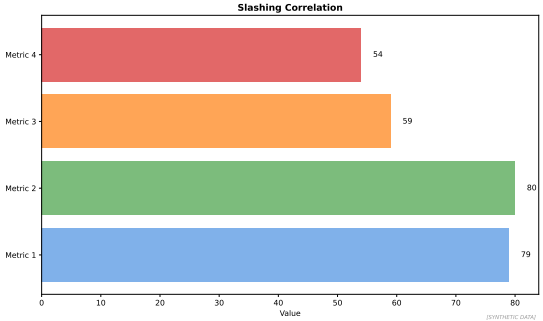
# Slashing Correlation Penalty




**Formula:**

$$\text{Penalty} = \text{Base} + \text{Stake} \times \frac{\text{Slashed Validators}}{\text{Total Validators}} \times 3$$

**Example:** If 33% of validators slashed together, each loses entire stake

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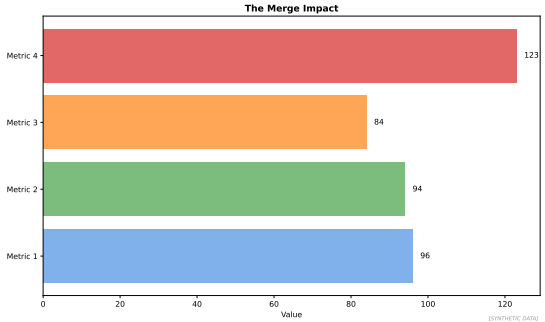
# The Merge: Ethereum's Transition (Sept 15, 2022)

**Before:**

- Proof of Work (since 2015)
- Energy: ∼78 TWh/year
- Issuance: ∼13,000 ETH/day
- Block time: ∼13 seconds

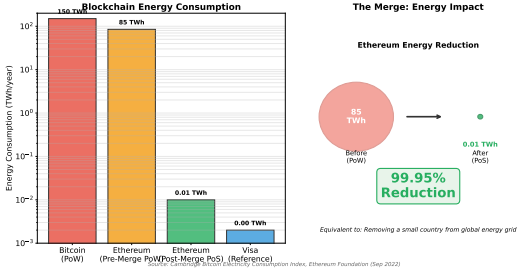
**After:**

- Proof of Stake
- Energy: ∼0.01 TWh/year (99.95% reduction)
- Issuance: ∼1,600 ETH/day (88% reduction)
- Block time: 12 seconds (fixed)




**Ethereum pioneered smart contracts and remains the dominant platform for DeFi and NFTs.**

# Environmental Impact: Before and After The Merge




**Comparison (Annualized):**

- **PoW Ethereum:** 78 TWh/year $\approx$ Chile's electricity consumption
- **PoS Ethereum:** 0.01 TWh/year $\approx$ 2,000 households
- **Per transaction:** PoW $\sim$200 kWh $\rightarrow$ PoS $\sim$0.01 kWh (20,000x improvement)

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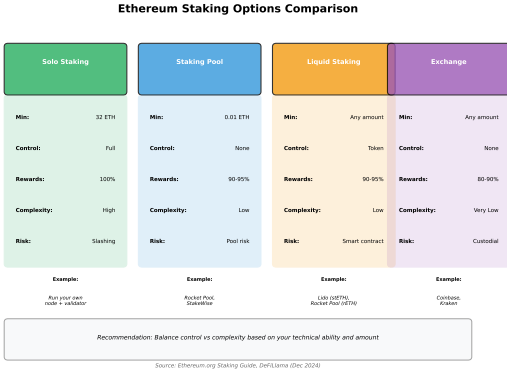
# Staking Economics: Solo vs Pooled




**Solo Staking:**

- 32 ETH minimum
- Full control, maximum rewards
- Technical expertise required
- Hardware costs

**Pooled/Liquid Staking:**

- Any amount (e.g., Lido, Rocket Pool)
- Receive staking derivative (stETH)
- Lower rewards (pool fees 10–15%)
- Easier, but centralization risk

**Comparative analysis helps identify the right tool for specific requirements.**

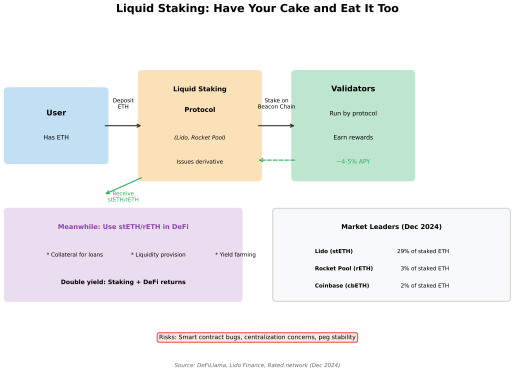
# Liquid Staking Derivatives (LSDs)

**Problem:**

- Staked ETH locked until withdrawals enabled
- Lost liquidity
- Opportunity cost

**Solution:**

- Deposit ETH, receive stETH (1:1)
- stETH accrues staking rewards
- Tradeable on DeFi markets
- Use as collateral




**Risks:** Centralization (Lido has >30% of staked ETH), smart contract risk, de-peg risk

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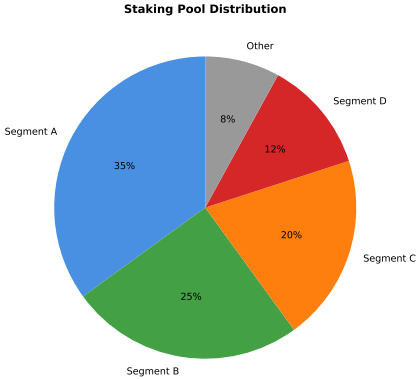
**Derivatives enable risk transfer and price discovery.**

# Lido Dominance: Centralization Concern

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**Concerns:**

- Lido controls >30% of staked ETH (as of 2024)
- Single point of failure for governance
- Risk of coordinated censorship

**Mitigation:** Self-limiting proposals, multi-operator model, community governance

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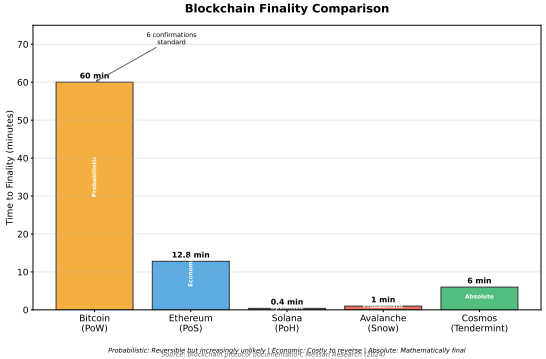
# Finality: Proof of Stake Advantage

**Proof of Work:**

- Probabilistic finality
- Never 100% certain
- 6 confirmations $\approx$ 1 hour (Bitcoin)
- Longest chain rule

**Proof of Stake (Ethereum):**

- Economic finality
- 2 epochs ($\sim$13 minutes)
- Reversion requires $>$50% stake loss
- Absolute finality




**Proof-of-Stake offers energy efficiency while maintaining decentralization.**

# Security Model: PoW vs PoS

| Aspect | Proof of Work | Proof of Stake |
|---|---|---|
| Attack Cost | Buy hashrate (hardware + electricity) | Acquire majority stake |
| Attack Aftermath | Can reuse hardware | Stake slashed, loses capital |
| Defense | Increase difficulty, dilute attacker hashrate | Slash attacker stake |
| Recovery | Continue mining normally | Coordination for hard fork |
| Long-Range Attack | Not possible (checkpoints) | Weak subjectivity needed |

**Key Difference:** PoS attacks destroy attacker's capital, PoW attacks do not

**Comparative analysis helps identify the right tool for specific requirements.**

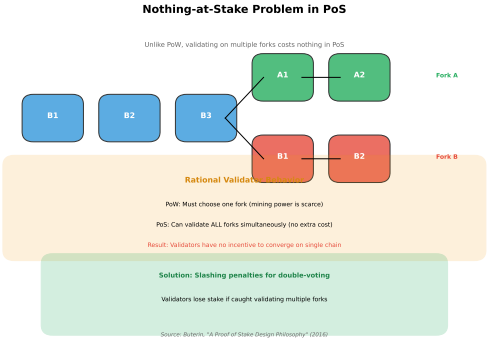
# Nothing-at-Stake Problem

**Problem:**

- In PoW, mining on two chains splits hashrate
- In PoS, validating on two chains costs nothing
- Rational to vote on all forks
- Prevents convergence

**Solution:**

- Slashing for double-voting
- Casper FFG rules (Ethereum)
- Economic penalties enforce single chain




**Key concepts from this slide inform practical applications in finance.**

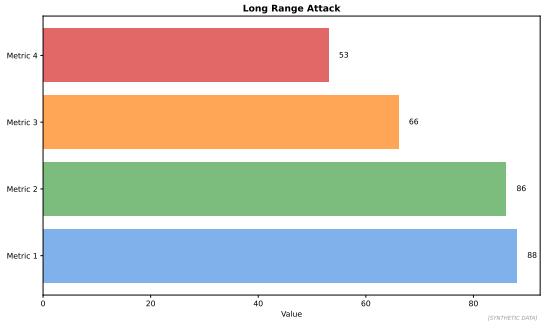
# Long-Range Attack and Weak Subjectivity

**Long-Range Attack:**

- Attacker acquires old private keys
- Rewrites history from genesis
- No computational cost (unlike PoW)
- Creates alternative chain

**Weak Subjectivity:**

- New nodes must checkpoint recent state
- Cannot sync from genesis alone
- Trusted source for initial sync
- Checkpoints updated periodically




**Security analysis identifies vulnerabilities and helps design robust systems.**

# Other PoS Implementations

| Chain | Consensus | Min Stake | Features |
|---|---|---|---|
| Ethereum | Casper FFG + LMD GHOST | 32 ETH | Slashing, finality |
| Cardano | Ouroboros | Any (pool delegation) | Peer-reviewed, formal verification |
| Polkadot | GRANDPA + BABE | 350 DOT (nominator) | Nominated PoS, parachains |
| Cosmos | Tendermint | Any (delegated) | Instant finality, IBC |
| Solana | Tower BFT | Any (delegated) | Proof of History hybrid |

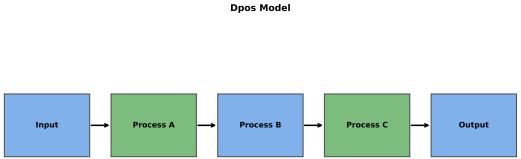
# Delegated Proof of Stake (DPoS)

**Mechanism:**

- Token holders vote for validators
- Limited validator set (21–100)
- Validators produce blocks in rotation
- Faster, more scalable

**Examples:**

- EOS (21 validators)
- Tron (27 validators)
- Cosmos Hub (175 validators)

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**Trade-off:** Performance vs decentralization (fewer validators = more centralized)

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**Proof-of-Stake offers energy efficiency while maintaining decentralization.**

# Criticisms of Proof of Stake

- **"Rich Get Richer":** Rewards proportional to stake, concentrates wealth
  - Counterargument: PoW also centralizes (economies of scale in mining)
- **Centralization:** Large staking pools (Lido >30% on Ethereum)
  - Counterargument: PoW mining pools also concentrated
- **Complexity:** Slashing, finality gadgets, weak subjectivity
  - Counterargument: Enables features impossible in PoW
- **Plutocracy:** Governance by wealthy token holders
  - Counterargument: Better than PoW's hardware oligopoly
- **Unproven:** Shorter track record than PoW
  - Counterargument: Ethereum's Merge successful so far (2+ years)

**Proof-of-Stake offers energy efficiency while maintaining decentralization.**

# Summary

- **Proof of Stake:** Replace computation with capital, 99.95% energy reduction
- **Validators:** Lock stake (32 ETH on Ethereum), earn rewards, slashed if malicious
- **The Merge (2022):** Ethereum transitioned PoW $\rightarrow$ PoS successfully
- **Finality:** 2 epochs ($\sim$13 min) for absolute finality vs probabilistic PoW
- **Challenges:** Centralization (Lido), nothing-at-stake, long-range attacks
- **Trade-offs:** Energy efficiency vs complexity, different trust assumptions

**Next Lesson:** Bitcoin Architecture – UTXO model and transaction mechanics