Blockchain Scalability Trilemma

BSc Blockchain, Crypto Economy & NFTs

Course Instructor

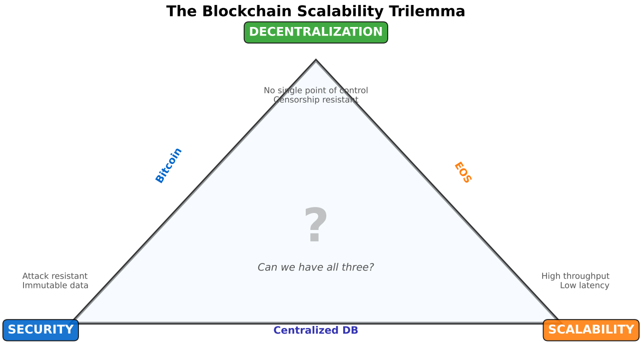
Module A: Blockchain Foundations

Learning Objectives

By the end of this lesson, you will be able to:

- Explain the blockchain scalability trilemma
- Analyze trade-offs between security, decentralization, and scalability
- Understand Layer 1 scalability bottlenecks
- Compare throughput limitations across blockchains
- Evaluate vertical vs. horizontal scaling approaches
- Recognize emerging scalability solutions

The Scalability Trilemma



Coined by Vitalik Buterin: a blockchain can achieve at most two of three properties.

Understanding the Trilemma

The Three Properties:

1. **Decentralization:** No single entity or small group controls the network
2. **Security:** Resistant to attacks, ensures data integrity
3. **Scalability:** High transaction throughput and low latency

Trade-Off Examples:

- Bitcoin: Decentralized + Secure → Low Scalability (7 TPS)
- EOS: Scalable + Secure → Low Decentralization (21 block producers)
- Centralized Database: Scalable + Secure → No Decentralization

Core Challenge:

- Larger blocks → fewer nodes can validate (centralization)
- Fewer validators → faster consensus (centralization)
- No free lunch: optimizing one property often degrades another

Why Each Property Matters

Decentralization

- Censorship resistance
- Fault tolerance
- Trustlessness
- No single point of failure

Security

- Immutability
- Double-spend prevention
- Attack resistance
- Data integrity

Scalability

- High throughput (TPS)
- Low latency (finality)
- Low transaction costs
- Mass adoption support

Why Blockchain Needs All Three:

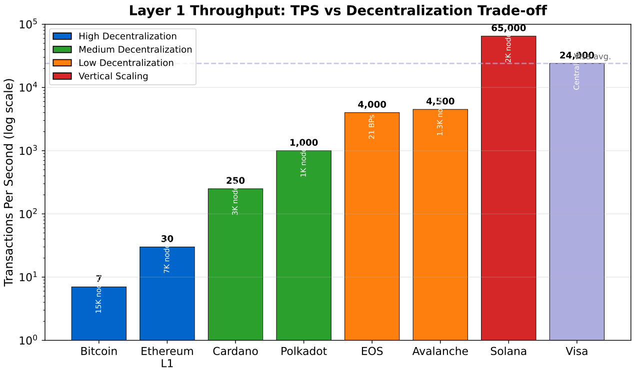
- DeFi applications need high throughput AND security
- Mass adoption requires scalability without sacrificing decentralization
- Competition with traditional payment systems (Visa: 24,000 TPS)

Layer 1 Bottlenecks

Fundamental Constraints:

1. **Block Size:**
   - Larger blocks = more TXs, but slower propagation, higher storage
   - Bitcoin: 1-4 MB — Ethereum: variable (gas limit)
2. **Block Time:**
   - Faster blocks = higher throughput, but more orphans/forks
   - Bitcoin: 10 min — Ethereum: 12 sec — Solana: 0.4 sec
3. **State Growth:**
   - Bitcoin: ~500 GB — Ethereum: ~1 TB (archive)
   - Full nodes require significant storage
4. **Computational Overhead:**
   - Every node verifies every transaction
   - Smart contracts computationally expensive

Layer 1 Throughput Comparison



Inverse correlation: higher TPS generally means fewer nodes and lower decentralization.

The Block Size Debate: Bitcoin Case Study

Background:

- Bitcoin originally: 1 MB block size limit
- As adoption grew: blocks filled up → higher fees, slower confirmations

Big Block Proponents:

- Increase to 8 MB, 32 MB, or unlimited
- Immediate throughput increase, low fees
- Risk: centralization (fewer can run full nodes)

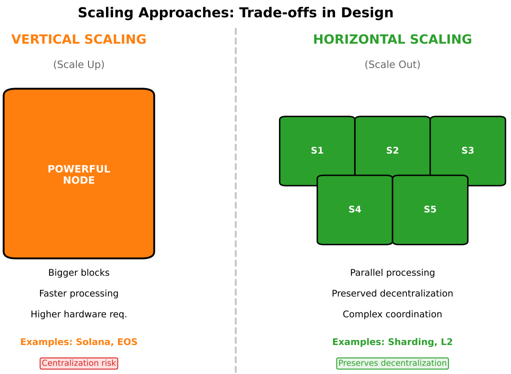
Small Block Proponents:

- Keep blocks small to preserve decentralization
- Scale via Layer 2 (Lightning Network)
- Accept higher on-chain fees

Outcome (2017):

- Bitcoin Cash hard fork (8 MB blocks)
- Bitcoin: SegWit soft fork (effective 1-4 MB)
- Market verdict: BTC prioritized decentralization, price ¿ BCH

Vertical vs. Horizontal Scaling



Most major blockchains pursue horizontal scaling to preserve decentralization.

Scaling Approaches Explained

Vertical Scaling (Scale Up)

- Increase capacity of individual nodes
- Require more powerful hardware
- Examples: Solana, EOS

Advantages:

- Simpler implementation
- Immediate throughput gains

Disadvantages:

- Raises barrier to run nodes
- Centralization risk
- Hits physical limits

Horizontal Scaling (Scale Out)

- Distribute load across many nodes
- Parallel processing
- Examples: Sharding, Layer 2, Rollups

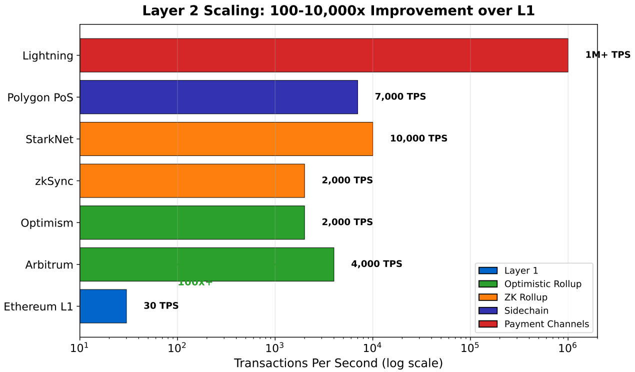
Advantages:

- Preserves decentralization
- Theoretically unbounded scaling

Disadvantages:

- Complex implementation
- Cross-shard communication overhead
- Longer development timelines

Layer 2 Scaling Solutions



Layer 2 achieves 100-10,000x improvement while inheriting L1 security.

Layer 2 Types

1. Payment Channels (Lightning Network):

- Open channel with on-chain TX, unlimited off-chain TXs
- Use case: micropayments, instant transfers
- TPS: theoretically unlimited

2. Rollups (Optimistic, ZK):

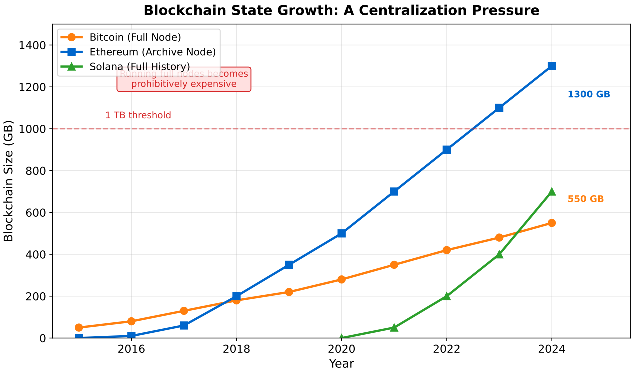
- Bundle hundreds of transactions into one
- Optimistic: assume valid, fraud proofs challenge
- ZK: cryptographic validity proofs
- Use case: DeFi, NFTs, general computation

3. Sidechains (Polygon):

- Independent blockchain with bridge to main chain
- Own consensus mechanism
- Weaker security than rollups (separate validator set)

Current Adoption: Ethereum L2 TVL: $40B+ (2024)

State Growth Problem



Running full nodes becomes prohibitively expensive as state grows.

State Growth Solutions

Challenge:

- Blockchain size grows unbounded
- Ethereum state: ~100 GB (accounts, storage)
- Syncing new nodes takes days/weeks
- Centralization pressure (only dedicated users run nodes)

Solutions:

1. **State Expiry (Ethereum proposal):**
   - Inactive state evicted from active storage
   - Must provide proof to re-activate
2. **Pruning:**
   - Discard old blockchain history
   - Keep only recent blocks + current state
3. **Rent (Cosmos, EOS):**
   - Users pay ongoing fees to store state
   - Incentivizes cleanup of unused data

Sharding: Horizontal Scaling at Layer 1

Concept:

- Split blockchain into parallel “shards”
- Each shard processes subset of transactions
- Aggregate throughput = shards $\times$ per-shard TPS

Ethereum Sharding Roadmap:

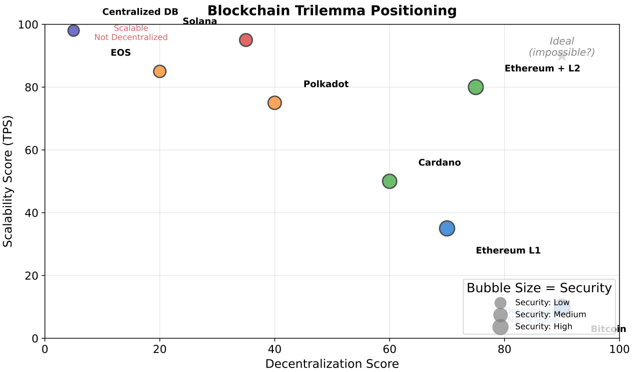
- Current plan: data availability sharding (danksharding)
- EIP-4844 proto-danksharding deployed March 2024
- Target: 100,000+ TPS via rollups + sharding

Challenges:

- Cross-shard communication complexity
- Shard takeover attacks (low-stake shards vulnerable)
- State management (which shard holds which data?)

Other Sharded Chains: Zilliqa, NEAR Protocol, Elrond

Trilemma Positioning



Ethereum + L2 approaches the "ideal" corner without sacrificing security.

Breaking the Trilemma: Possible?

Optimistic View:

- Layer 2 separates execution from settlement
- Rollups achieve scalability without sacrificing L1 security
- Data availability sampling enables sharding
- Zero-knowledge proofs compress computation

Pessimistic View:

- Layer 2 introduces new trust assumptions (sequencers, bridges)
- Increased complexity $\rightarrow$ more attack vectors
- Still bound by data availability bandwidth

Consensus View:

- Trilemma remains but can be mitigated
- Modular architecture (separate execution, consensus, DA)
- Accept specialization: L1 for security, L2 for scale
- Not "solving" trilemma but "navigating" it intelligently

Key Takeaways

- Scalability trilemma: cannot maximize decentralization, security, and scalability simultaneously
- Layer 1 bottlenecks: block size, block time, state growth
- Vertical scaling (bigger nodes) increases centralization
- Horizontal scaling (sharding, Layer 2) preserves decentralization
- Layer 2 solutions achieve 100-1000x throughput improvement
- State growth threatens long-term node decentralization
- Real-world TPS often far below theoretical limits

Design Philosophy:
Accept that trade-offs exist. Bitcoin prioritizes decentralization/security. Solana prioritizes scalability. Ethereum aims for balance via Layer 2.

Discussion Questions

1. Why cannot a blockchain simply increase block size indefinitely?
2. How do Layer 2 solutions differ from sidechains in terms of security?
3. What are the implications of state growth for decentralization?
4. Can the trilemma be "solved" or only mitigated?
5. How does sharding introduce new security challenges?
6. Why do most blockchains have lower actual TPS than theoretical TPS?

Next Lesson Preview: L12 Lab - Block Explorer Analysis

Lab activities:

- Navigate Etherscan and Blockstream block explorers
- Analyze transaction details (inputs, outputs, fees, confirmations)
- Trace transaction lifecycle from mempool to confirmation
- Examine block structure (header, transactions, miner rewards)
- Practice forensic blockchain analysis

Preparation:

- Review Bitcoin transaction structure (Lesson 6)
- Ensure access to Etherscan.io and Blockstream.info