

Blockchain Scalability Trilemma

BSc Blockchain, Crypto Economy & NFTs

Course Instructor

Module A: Blockchain Foundations

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 Problem: How do we scale blockchains?

The Challenge

Blockchains face a fundamental limitation: achieving global-scale transaction throughput while preserving decentralization and security. Bitcoin processes 7 TPS while Ethereum handles 15 TPS—far below the requirements for mass adoption or competition with traditional payment systems.

Why It Matters

- Bitcoin: 7 TPS vs. Visa: 65,000 TPS—blockchains cannot serve billions of users
- Ethereum's 2017 CryptoKitties congestion halted the network, with gas prices spiking 1000%

What We Need

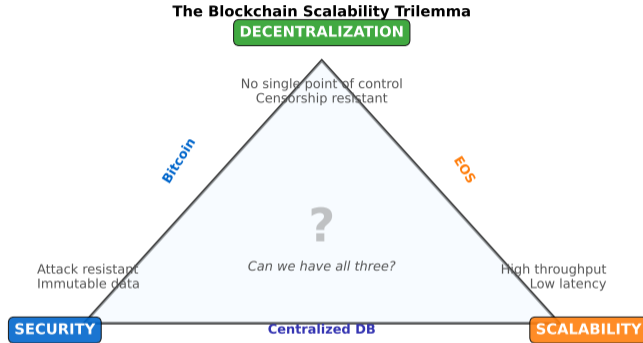
- Understanding design constraints
- Scale to handle global transaction volumes without sacrificing decentralization or security

The Cryptoeconomics Question

How do we optimize for competing goals: throughput, decentralization, and security?

Today's lesson: How the Scalability Trilemma framework addresses this challenge

The Scalability Trilemma



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

Three Properties:

- **Decentralization:** No single controller
- **Security:** Attack resistant
- **Scalability:** High TPS, low latency

Trade-Offs:

- BTC: Decentral + Secure = 7 TPS
- EOS: Scale + Secure = 21 nodes
- DB: Scale + Secure = centralized

Core Challenges:

- Large blocks = fewer validators
- Fewer validators = faster consensus
- Optimizing one degrades others

Key Insight:

No free lunch - trade-offs are fundamental

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)

Block Size:

- Larger = more TXs, slower propagation
- BTC: 1-4 MB — ETH: gas limit

Block Time:

- Faster = more orphans/forks
- BTC: 10m — ETH: 12s — SOL: 0.4s

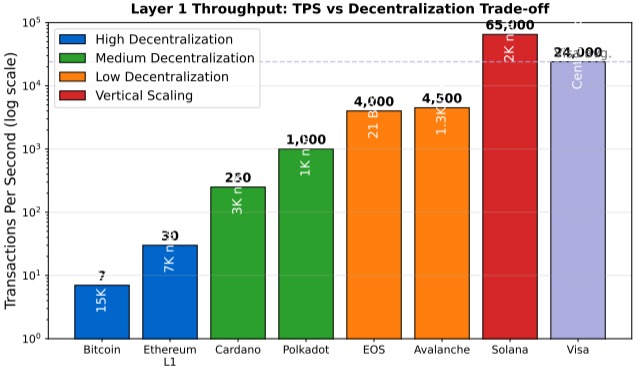
State Growth:

- BTC: 500 GB — ETH: 1 TB
- Full nodes need storage

Computation:

- Every node verifies all TXs
- Smart contracts expensive

Layer 1 Throughput Comparison



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

Big Block Camp:

- Increase to 8+ MB
- Higher throughput, low fees
- Risk: centralization

Small Block Camp:

- Preserve decentralization
- Scale via Layer 2
- Accept higher on-chain fees

Outcome (2017):

- BCH fork: 8 MB blocks
- BTC: SegWit (1-4 MB)
- Market: BTC > BCH

Lesson:

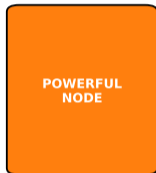
Decentralization prioritized; Layer 2 for scale

Vertical vs. Horizontal Scaling

Scaling Approaches: Trade-offs in Design

VERTICAL SCALING

(Scale Up)



Bigger blocks
Faster processing
Higher hardware req.

Examples: Solana, EOS

Centralization risk

HORIZONTAL SCALING

(Scale Out)



Parallel processing
Preserved decentralization
Complex coordination

Examples: Sharding, L2

Preserves decentralization

Most major blockchains pursue horizontal scaling to preserve decentralization.

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

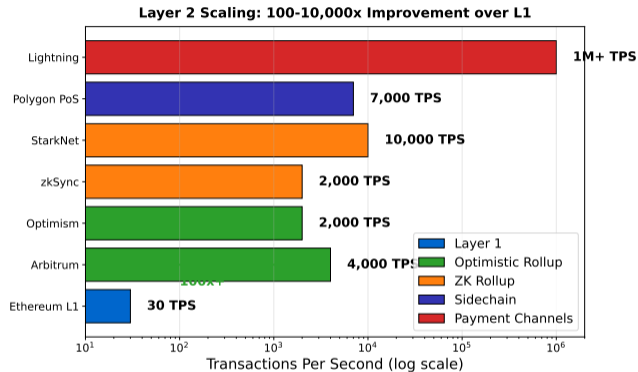
Advantages:

- 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.

Payment Channels:

- Lightning Network
- 1 on-chain, unlimited off-chain
- Micropayments

Rollups:

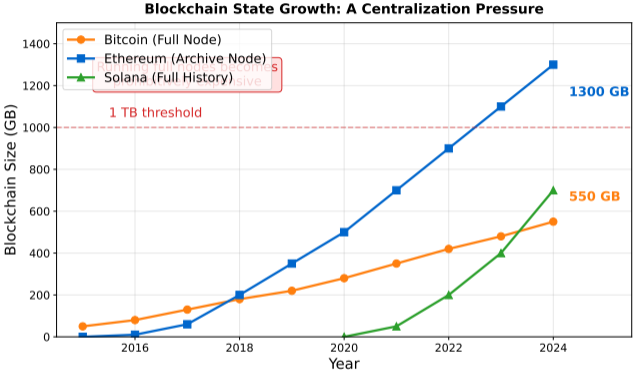
- Bundle 100s of TXs
- Optimistic: fraud proofs
- ZK: validity proofs

Sidechains:

- Independent chain
- Own consensus
- Weaker security

Adoption: Ethereum L2 TVL \$54B+ (Dec 2024, 205% YoY)

State Growth Problem



Running full nodes becomes prohibitively expensive as state grows.

Challenge:

- Unbounded growth
- ETH state: 100 GB
- Sync takes days/weeks
- Centralization pressure

Solutions:

- **State Expiry:** evict inactive, proof to recover
- **Pruning:** keep recent blocks only
- **Rent:** pay to store (Cosmos, EOS)

Concept:

- Split into parallel shards
- Each processes subset of TXs
- Total TPS = shards x per-shard

Ethereum Roadmap:

- Danksharding for DA
- EIP-4844 (March 2024)
- Target: 100K+ TPS

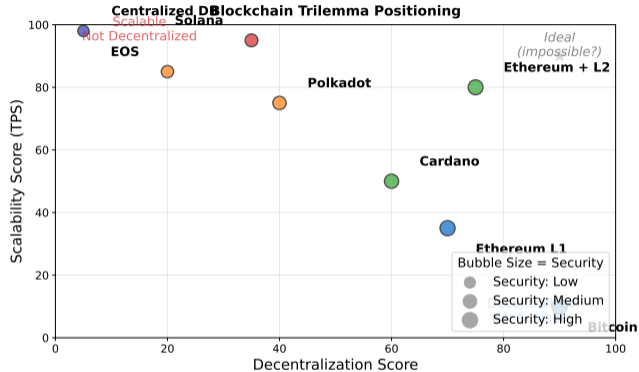
Challenges:

- Cross-shard complexity
- Shard takeover attacks
- State management

Other Chains:

Zilliqa, NEAR, Elrond

Trilemma Positioning



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

Breaking the Trilemma: Possible?

Optimistic:

- L2 separates layers
- Rollups keep security
- ZK compresses compute

Pessimistic:

- L2 adds trust
- More complexity
- DA bandwidth limits

Consensus:

- Mitigate, not solve
- Modular design
- L1 security, L2 scale

Navigate the trilemma intelligently rather than "solve" it

Problem Solved? Scalability Trilemma

The Original Problem

How do we scale blockchains to handle global transaction volume?

How Scalability Solutions Address It

- **Layer 2 solutions (rollups, state channels):** Move computation off-chain, achieve 100-10,000x throughput improvement while inheriting L1 security
- **Sharding:** Split state across parallel chains, enabling horizontal scaling to theoretically unbounded throughput
- **Modular design:** Separate consensus, data availability, and execution layers to optimize each independently

Remaining Limitations

- **Layer 2 introduces new trust assumptions:** Sequencer centralization, bridge security risks, and withdrawal delays
- **Trade-off made:** Increased complexity and fragmented liquidity in exchange for higher throughput

Open Questions

- Will rollups or sharding dominate as the long-term scaling solution?
- Risk: Over-optimization for single metric

Scalability Trilemma framework helps navigate trade-offs but doesn't eliminate fundamental constraints

Trilemma:

- Cannot maximize all three
- L1: block size, time, state
- Vertical = centralization
- Horizontal = decentralization

Solutions:

- L2: 100-1000x throughput
- State growth = risk
- Real TPS \neq theoretical

Philosophy:

BTC: decentral — SOL: scale — ETH: L2 balance

- 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?

Lab Activities:

- Navigate Etherscan, Blockstream
- Analyze TX details
- Trace mempool to confirmation
- Examine block structure
- Forensic analysis

Preparation:

- Review L6 TX structure
- Access Etherscan.io
- Access Blockstream.info

Quiz Questions (1/4)

Q1. What is the blockchain scalability trilemma?

- A) The choice between PoW, PoS, and DPoS
- B) Achieving only two of: decentralization, security, scalability
- C) The trade-off between speed and cost
- D) The conflict between miners and validators

Answer: B – The trilemma states a blockchain can optimize at most two of three properties simultaneously.

Q2. Why does increasing block size lead to centralization?

- A) It reduces miner rewards
- B) Fewer nodes can store/propagate large blocks
- C) It makes attacks easier
- D) It decreases transaction fees

Answer: B – Larger blocks require more bandwidth and storage, raising barriers to running full nodes.

Q3. Bitcoin processes approximately how many transactions per second (TPS)?

- A) 3 TPS
- B) 7 TPS
- C) 30 TPS
- D) 100 TPS

Answer: B – Bitcoin's design prioritizes decentralization and security over throughput.

Q4. What is vertical scaling in blockchain context?

- A) Adding more nodes to the network
- B) Increasing capacity of individual nodes
- C) Creating Layer 2 solutions
- D) Implementing sharding

Answer: B – Vertical scaling means requiring more powerful hardware per node.

Q5. Which blockchain outcome resulted from the 2017 block size debate?

- A) Ethereum Classic fork
- B) Bitcoin Cash fork with larger blocks
- C) Bitcoin unlimited blocks
- D) Complete consensus on 8 MB blocks

Answer: B – Bitcoin Cash forked with 8 MB blocks while Bitcoin implemented SegWit.

Quiz Questions (2/4)

Q6. What is the primary advantage of Layer 2 solutions?

- A) Complete decentralization
- B) Higher throughput while inheriting L1 security
- C) Lower hardware requirements
- D) Simpler code implementation

Answer: B – Layer 2 achieves 100-10,000x scalability while settling to secure Layer 1.

Q7. How does horizontal scaling differ from vertical scaling?

- A) It uses better hardware
- B) It distributes load across many nodes/shards
- C) It reduces security
- D) It eliminates the need for consensus

Answer: B – Horizontal scaling parallelizes processing to preserve decentralization.

Q8. What is sharding?

- A) Compressing blockchain data
- B) Splitting blockchain into parallel processing shards
- C) Encrypting transactions
- D) A type of consensus algorithm

Answer: B – Sharding divides the network to process transactions in parallel.

Q9. Which Layer 2 solution uses fraud proofs?

- A) ZK-Rollups
- B) Payment channels
- C) Optimistic Rollups
- D) Sidechains

Answer: C – Optimistic Rollups assume validity and allow challenges via fraud proofs.

Q10. What is the state growth problem?

- A) Blockchain size growing unbounded over time
- B) Decreasing transaction volume
- C) Fewer validators joining
- D) Rising energy consumption

Answer: A – As blockchain accumulates data, storage requirements create centralization pressure.

Quiz Questions (3/4)

Q11. How do ZK-Rollups validate transactions?

- A) Through fraud proofs
- B) Using cryptographic validity proofs
- C) By running full nodes
- D) Through validator voting

Answer: B – ZK-Rollups use zero-knowledge proofs to guarantee transaction validity.

Q12. What was Ethereum's EIP-4844 proto-danksharding (March 2024)?

- A) Full execution sharding
- B) Data availability sharding to reduce L2 costs
- C) Transition to PoS
- D) Gas fee elimination

Answer: B – Proto-danksharding adds blob transactions for cheaper L2 data availability.

Q13. Which property does Bitcoin prioritize over scalability?

- A) Speed and cost
- B) Decentralization and security
- C) Smart contract flexibility
- D) Energy efficiency

Answer: B – Bitcoin's design maintains decentralization and security at the cost of throughput.

Q14. What is the main security concern with sidechains?

- A) They are too slow
- B) They have separate validator sets (weaker security)
- C) They cannot process smart contracts
- D) They require PoW consensus

Answer: B – Sidechains do not inherit L1 security guarantees like rollups do.

Q15. How does the Lightning Network achieve high throughput?

- A) Larger blocks
- B) Off-chain transactions in payment channels
- C) Faster block times
- D) More miners

Answer: B – Lightning opens channels with one on-chain TX, then unlimited off-chain payments.

Q16. What is state expiry in Ethereum's roadmap?

- A) Deleting old transactions
- B) Evicting inactive state, requiring proofs to re-activate
- C) Eliminating smart contracts
- D) Reducing gas fees to zero

Answer: B – State expiry removes inactive data to limit state growth while allowing recovery.

Q17. Why is cross-shard communication challenging?

- A) It requires complex coordination between shards
- B) It eliminates security
- C) It is impossible to implement
- D) It reduces decentralization

Answer: A – Transactions spanning shards need atomic execution and additional overhead.

Q18. Which blockchain has approximately 65,000 theoretical TPS?

- A) Bitcoin
- B) Ethereum
- C) Solana
- D) Cardano

Answer: C – Solana uses vertical scaling with high hardware requirements to achieve high TPS.

Q19. What is the Total Value Locked (TVL) in Ethereum Layer 2 solutions as of late 2024?

- A) \$5 billion
- B) \$50+ billion
- C) \$200 billion
- D) \$500 billion

Answer: B – Ethereum L2 TVL reached \$54B by Dec 2024 (205% YoY growth).

Q20. Can the scalability trilemma be fully "solved"?

- A) Yes, with sharding
- B) Yes, with Layer 2
- C) No, only mitigated through trade-offs
- D) Yes, Solana solved it

Answer: C – The trilemma represents fundamental trade-offs; solutions mitigate but don't eliminate them.