

## Lesson 1: What is Blockchain?

Module A: Blockchain Foundations

MSc Blockchain & Cryptocurrency

Digital Finance Program

2025

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

1. Define blockchain as a cryptographically-secured distributed ledger
2. Trace the historical evolution from 1991 to 2025
3. Explain the double-spending problem and its consensus-based solution
4. Formalize the hash chain structure:  $H(B_n) = H(\text{header}_n || \text{prev\_hash}_{n-1})$
5. Compare centralized, decentralized, and distributed architectures

**Prerequisites:** Cryptographic hash functions, basic probability theory

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**MSc level: Full mathematical rigor expected in subsequent slides**

# Formal Definition of Blockchain

## Mathematical Definition

A blockchain  $\mathcal{B}$  is an ordered sequence of blocks:

$$\mathcal{B} = (B_0, B_1, \dots, B_n)$$

Where each block  $B_i$  contains:

- Header  $h_i$  with metadata (version, timestamp, nonce, difficulty)
- Transaction set  $T_i = \{tx_1, \dots, tx_k\}$
- Hash pointer to previous block:  $H(B_{i-1})$

**Integrity Constraint:**

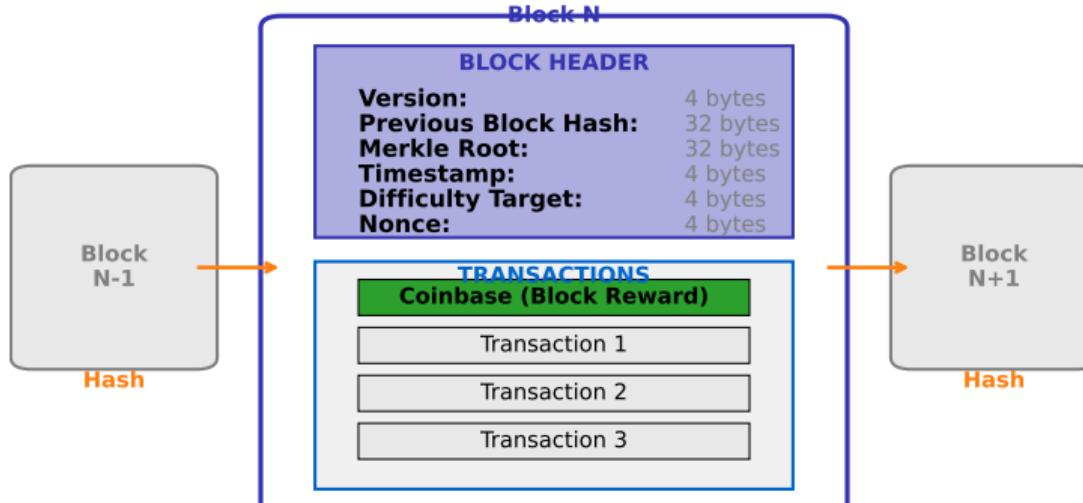
$$\forall i > 0 : B_i.\text{prev} = H(B_{i-1})$$

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The hash pointer creates a tamper-evident linked data structure

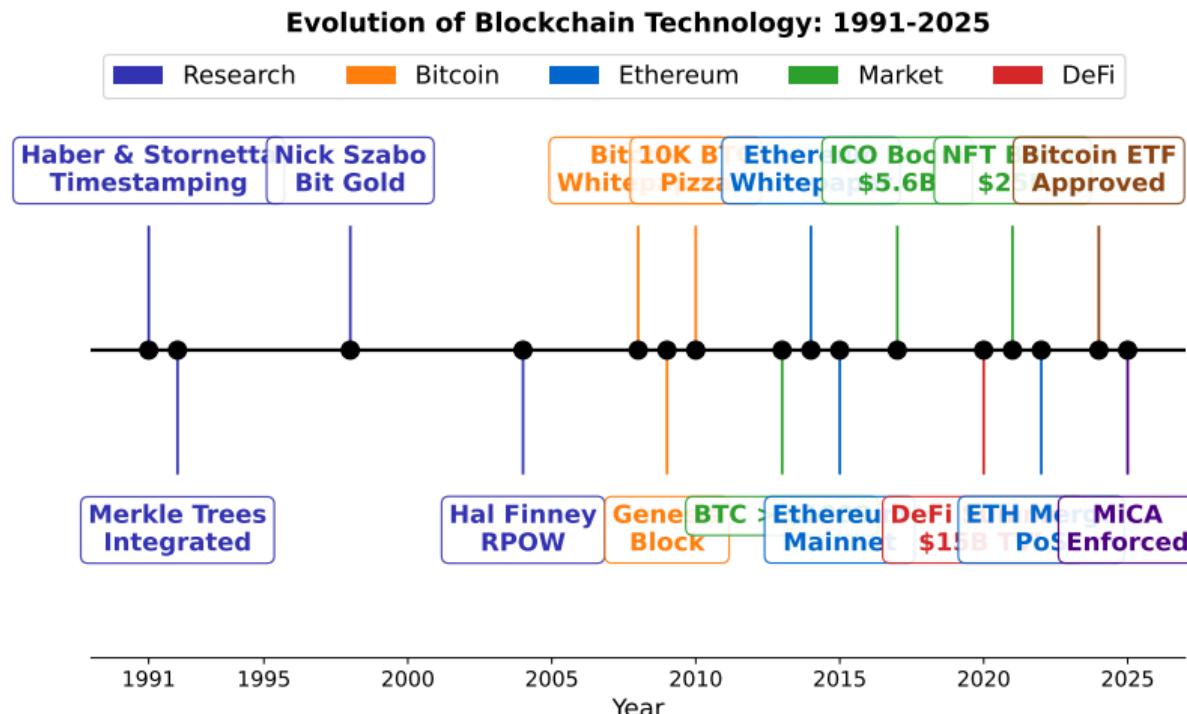
# Anatomy of a Blockchain Block

## Anatomy of a Blockchain Block

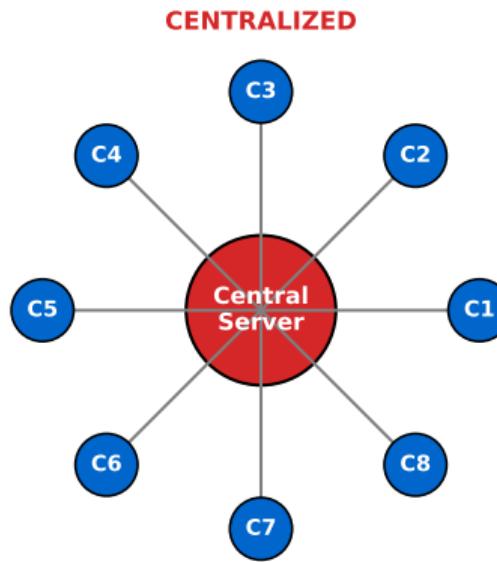


Bitcoin block header: 80 bytes — Block body: 1-2 MB of transactions

# Historical Evolution: 1991–2025



Key inflection points: 2008 (Nakamoto), 2015 (Ethereum), 2024 (Bitcoin ETFs)



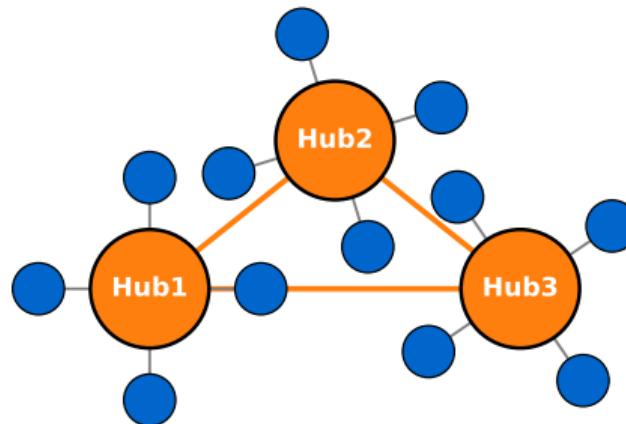
*Single point of failure | High throughput (~ $10^6$  TPS) | <10ms latency*

**Characteristics:** Single authority,  $10^6$  TPS, <10ms latency

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**Traditional systems:** banks, exchanges, cloud services

## DECENTRALIZED



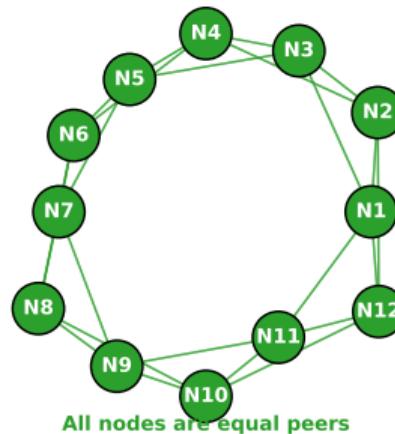
*Multiple hubs | Federation trust |  $\sim 10^3$  TPS |  $\sim 1s$  latency*

**Characteristics:** Multiple hubs, federated trust,  $10^3$  TPS

**Examples:** Federated exchanges, consortium blockchains

# Distributed Architecture (Blockchain)

## DISTRIBUTED (Blockchain)



No single point of failure | Cryptographic trust | ~10 TPS | ~10 min finality

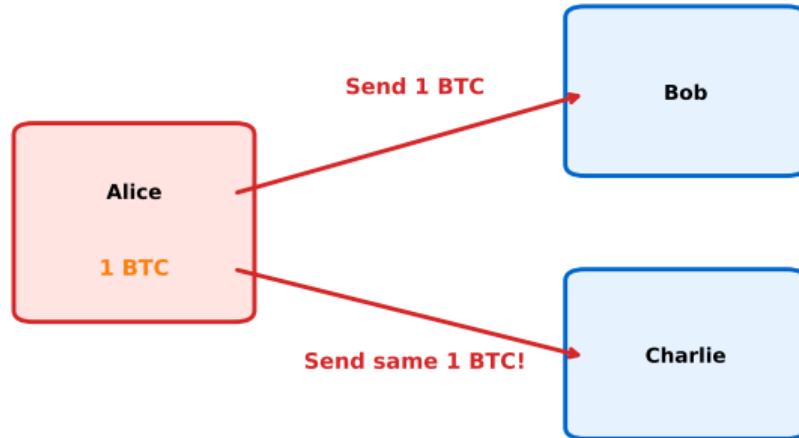
**Characteristics:** No hierarchy, cryptographic trust,  $10^1$  TPS

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Blockchain trades performance for trustlessness

# The Double-Spending Problem

THE PROBLEM: Digital files can be copied



**Problem:** Prevent  $\text{Transfer}(a, A \rightarrow B) \wedge \text{Transfer}(a, A \rightarrow C)$

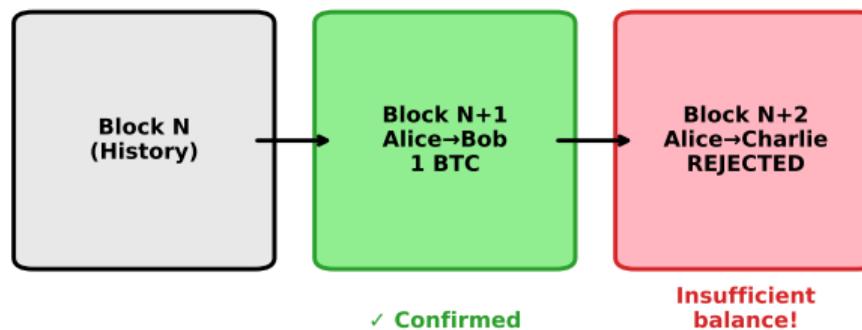
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Digital files can be copied infinitely — no inherent scarcity in bits

# The Blockchain Solution

## THE SOLUTION: Blockchain Ordering

*First valid transaction wins — Network consensus determines order*

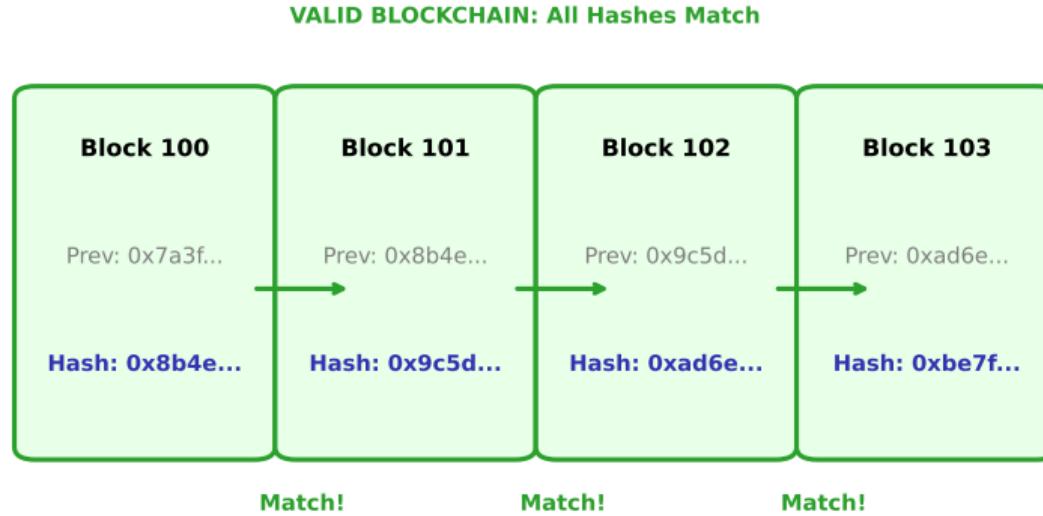


**Solution:** Distributed consensus determines transaction ordering

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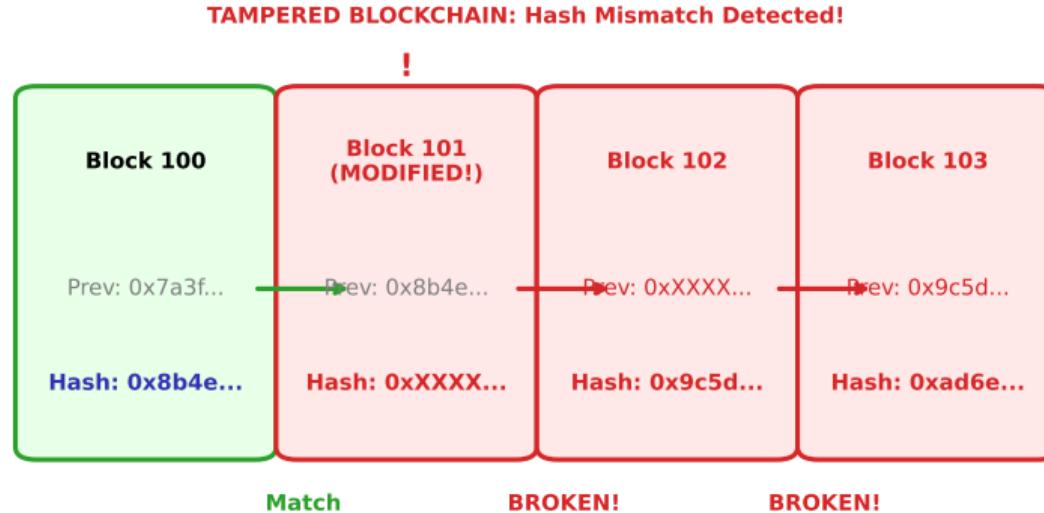
Nakamoto's key insight: Use computational work to achieve probabilistic finality

# Valid Blockchain: Hash Chain Integrity



Hash pointers create a tamper-evident linked data structure

# Tampered Blockchain: Detection



Modifying  $B_k$  requires recomputing all subsequent hashes:  $O(n - k) \times 2^{76}$  ops

# Merkle Tree: Efficient Transaction Verification

## Structure

Binary hash tree over transactions:

$$\text{Root} = H(H(H(tx_1) \parallel H(tx_2)) \parallel H(H(tx_3) \parallel H(tx_4)))$$

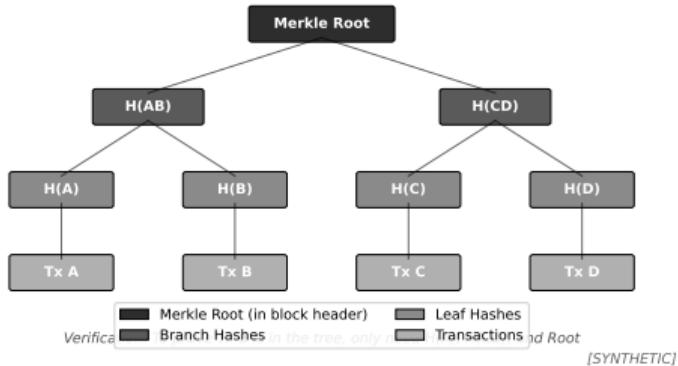
## Verification Complexity:

- Full verification:  $O(n)$  hashes
- Merkle proof:  $O(\log n)$  hashes
- SPV clients use proofs, not full chain

## Bitcoin Block Header:

32-byte Merkle root commits to all transactions

Merkle Tree: Efficient Transaction Verification



Merkle trees enable lightweight clients: verify transactions without downloading full blocks

## Cryptographic Properties

- **Collision Resistance:**

$$\Pr[H(x) = H(y) \wedge x \neq y] \approx 2^{-128}$$

- **Preimage Resistance:**

Given  $h$ , infeasible to find  $x : H(x) = h$

- **Avalanche Effect:**

1-bit change  $\Rightarrow$  50% output bits flip

**Probability of Reversal** (after  $k$  confirmations, attacker with  $q < 0.5$  hashrate):

$$P(\text{reversal}) < \left( \frac{q}{1-q} \right)^k$$

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6 confirmations  $\Rightarrow$  reversal probability  $< 0.1\%$  for  $q = 0.3$

## System Properties

- **Liveness:**

Valid transactions eventually confirmed

- **Safety:**

No double-spends with  $> k$  confirmations

- **Consistency:**

All honest nodes agree on prefix

## Finance & Payments

- Bitcoin: \$1.2T market cap, \$50B daily volume
- Stablecoins: USDT/USDC \$150B+ circulation
- DeFi TVL: \$80B across protocols
- Bitcoin ETFs: \$50B+ AUM (Jan 2024 launch)

## Enterprise

- IBM Food Trust: 500+ organizations
- JPMorgan Onyx: \$1B+ daily settlements
- Maersk TradeLens: 1.5B shipping events

## Government & CBDC

- China e-CNY: 260M+ wallets
- EU Digital Euro: Pilot phase 2024
- 130+ countries exploring CBDCs

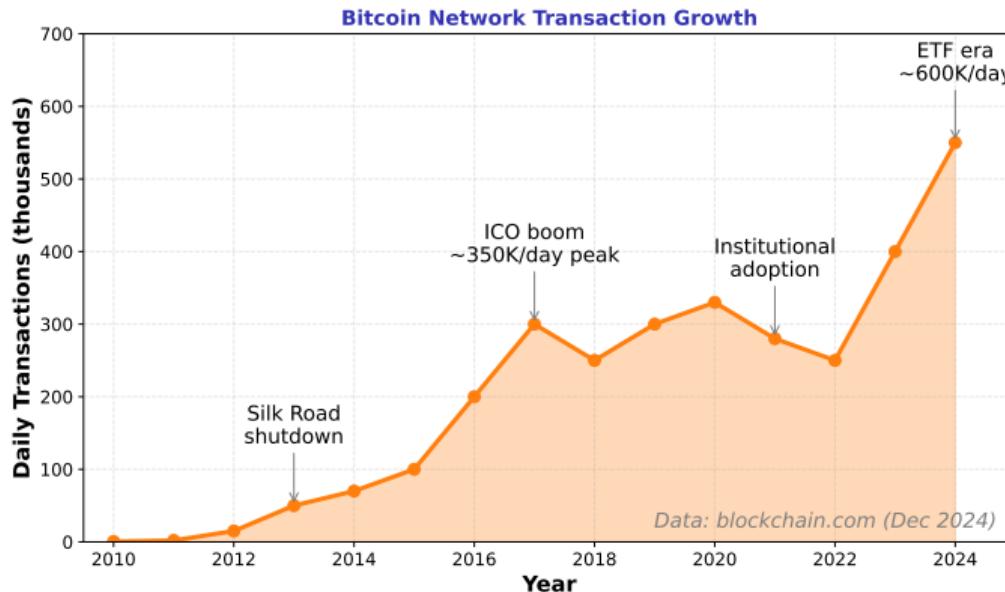
## Emerging Applications

- Real-World Assets (RWA): \$5B+ tokenized
- Decentralized Identity (DID)
- Supply chain provenance
- Carbon credit verification

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Source: DeFi Llama, CoinGecko, Atlantic Council CBDC Tracker (Dec 2024)

# Network Adoption: Bitcoin Transactions

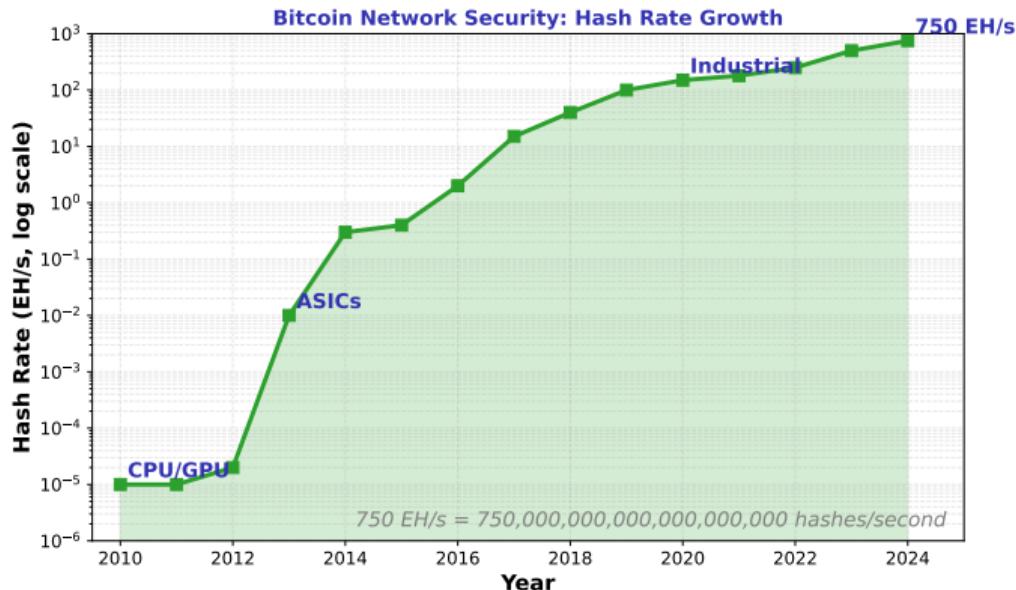


From <1K daily transactions (2010) to >600K daily (2024)

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Transaction volume indicates real economic activity on the network

# Network Security: Hash Rate Growth

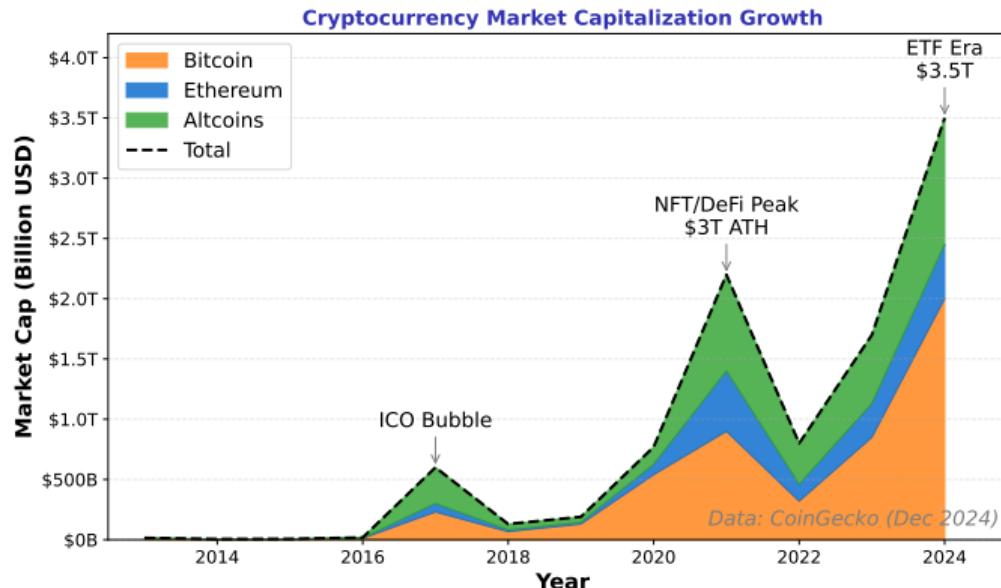


$750 \text{ EH/s} = 7.5 \times 10^{20} \text{ SHA-256 hashes per second}$

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**Higher hash rate = more computational cost to attack the network**

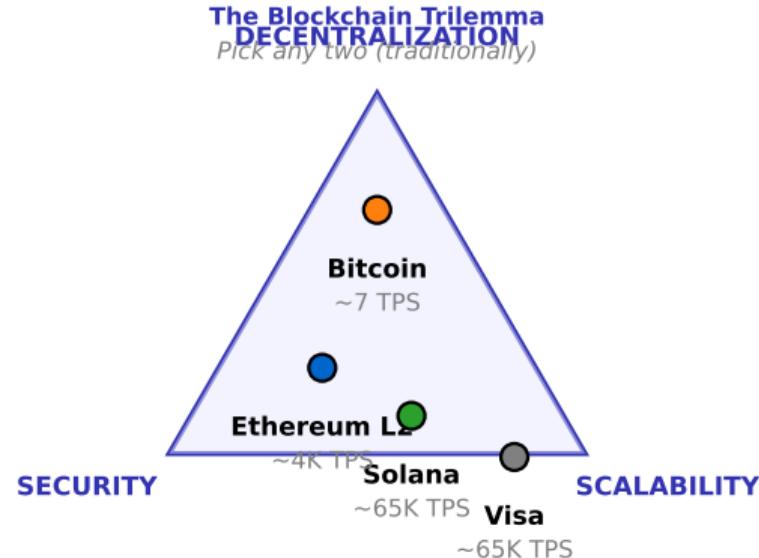
# Market Growth: Cryptocurrency Capitalization



Total market cap: \$3.5T (Dec 2024); Bitcoin dominance: ~57%

Market cap growth reflects institutional adoption and mainstream acceptance

# The Blockchain Trilemma



Layer 2 solutions attempt to optimize all three dimensions

# Decision Framework: When to Use Blockchain

## Use Blockchain When:

- ✓ Multiple writers, no trusted party
- ✓ Immutable audit trail required
- ✓ Disintermediation creates value
- ✓ Censorship resistance needed
- ✓ Cross-organizational data sharing

## Use Traditional DB When:

- ✗ Single organization controls data
- ✗ High throughput required (>10K TPS)
- ✗ Data deletion/modification needed
- ✗ Strong privacy requirements
- ✗ Existing solutions work well

## Decision Heuristic:

$$\text{Blockchain Value} \propto \frac{\text{Trust Deficit} \times \text{Coordination Benefit}}{\text{Performance Requirements}}$$

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Most enterprise “blockchain” projects could use a replicated database

## Core Concepts:

1. Blockchain = hash-chained blocks + distributed consensus + cryptographic signatures
2. Double-spending solved via total ordering through consensus mechanism
3. Immutability achieved through computational intractability of hash chain modification
4. Trade-off: Performance  $\leftrightarrow$  Trustlessness  $\leftrightarrow$  Decentralization

## Mathematical Foundations:

- Hash functions:  $H : \{0,1\}^* \rightarrow \{0,1\}^{256}$  (SHA-256)
- Merkle trees:  $O(\log n)$  verification complexity
- Reversal probability: Exponential decay with confirmations

**Next Lesson:** L02 – Distributed Ledger Technology (DLT) deep dive

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**Blockchain is a tool, not a solution — evaluate against specific requirements**