Lesson 1: What is Blockchain?

Module A: Blockchain Foundations

MSc Blockchain & Cryptocurrency

Digital Finance Program

2025

Learning Objectives

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

MSc level: Full mathematical rigor expected in subsequent slides

Mathematical Definition

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

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

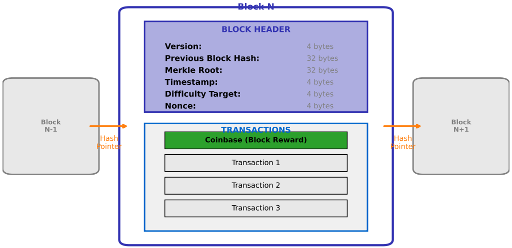
Where each block B_i contains:

- Header h_i with metadata
- Transaction set $T_i = \{tx_1, \ldots, tx_k\}$
- Hash pointer: $H(B_{i-1})$

Integrity Constraint:

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

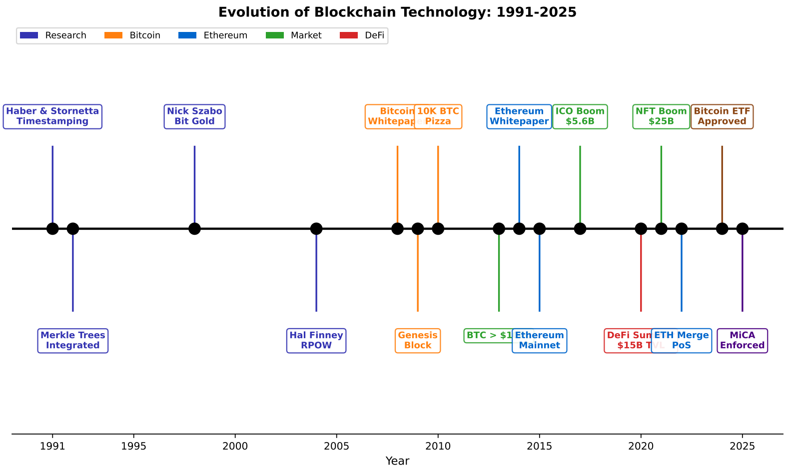
Anatomy of a Blockchain Block



Average Bitcoin block: ~1-2 MB | ~2000-3000 transactions

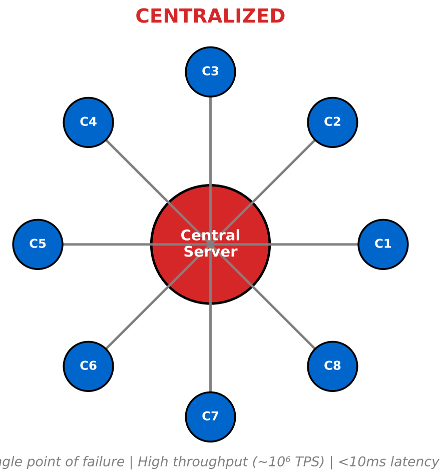
The hash pointer creates a tamper-evident data structure

Historical Evolution: 1991–2025



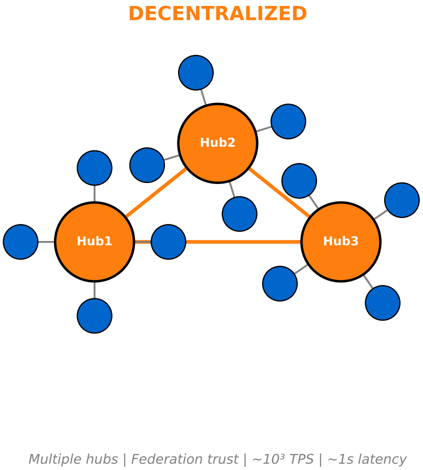
Key inflection points: 2008 (Nakamoto), 2015 (Ethereum), 2024 (Bitcoin ETFs)

Centralized Architecture



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

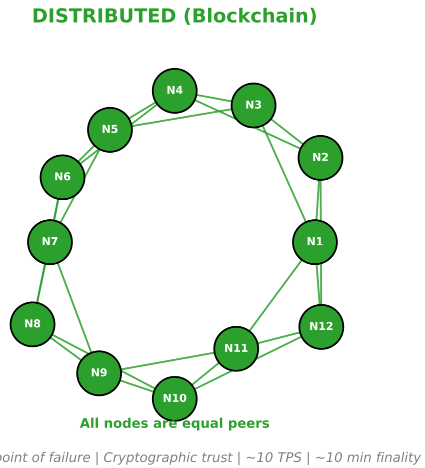
Traditional systems: banks, exchanges, cloud services



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

Examples: Federated exchanges, consortium blockchains

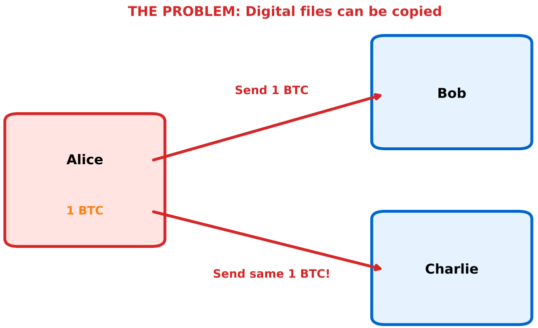
Distributed Architecture (Blockchain)



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

Blockchain trades performance for trustlessness

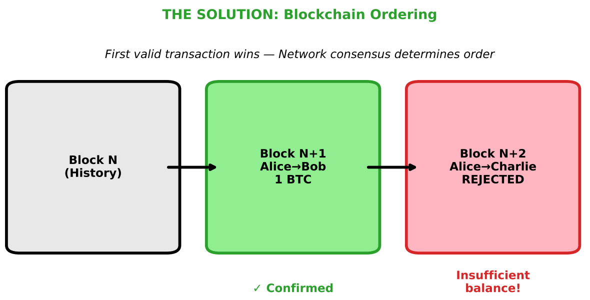
The Double-Spending Problem



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

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

The Blockchain Solution



Solution: Distributed consensus determines transaction ordering

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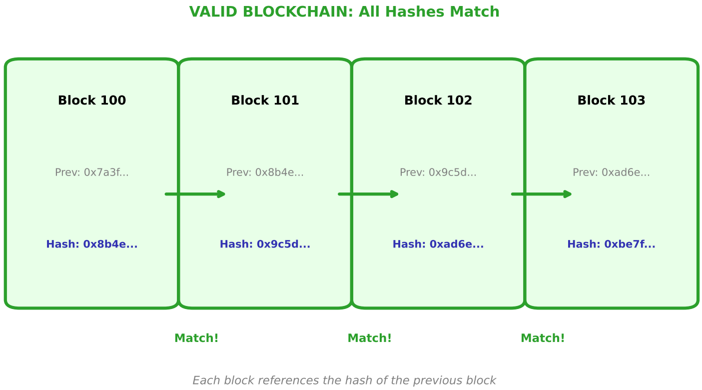
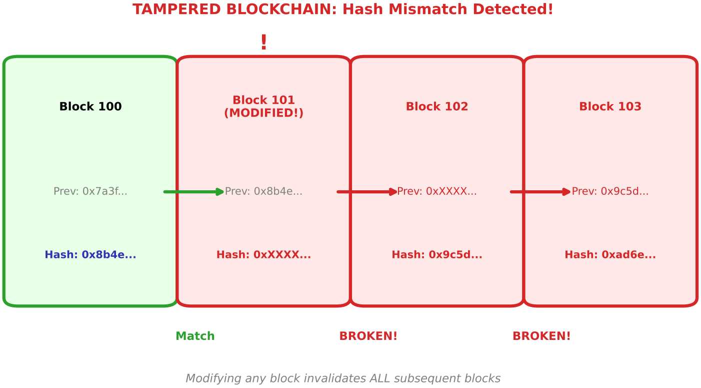
Nakamoto's key insight: Use computational work to achieve probabilistic finality

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

Structure

Binary hash tree over transactions:

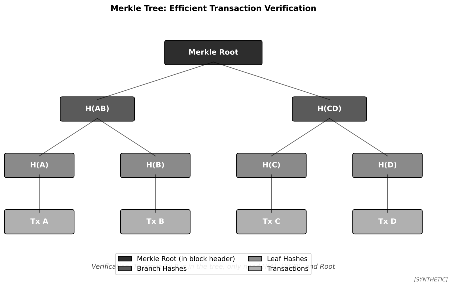
$$\text{Root} = H(H(H(tx_1)||H(tx_2))||H(H(tx_3)||H(tx_4)))$$

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 trees enable lightweight clients: verify transactions without downloading full blocks

Core Properties and Guarantees

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

System Properties

- **Liveness:**
  Valid transactions eventually confirmed
- **Safety:**
  No double-spends with $> k$ confirmations
- **Consistency:**
  All honest nodes agree on prefix

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

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

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

Real-World Applications (2025)

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

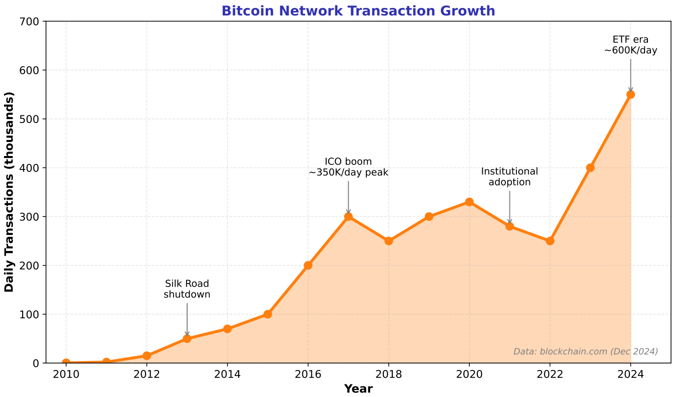
- China e-CNY: 260M+ wallets
- EU Digital Euro: Pilot phase 2024
- 130+ countries exploring CBDCs

Emerging Applications

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

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

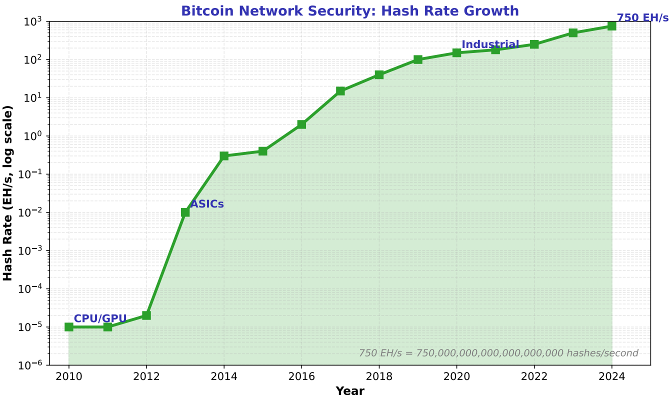
Network Adoption: Bitcoin Transactions



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

Transaction volume indicates real economic activity on the network

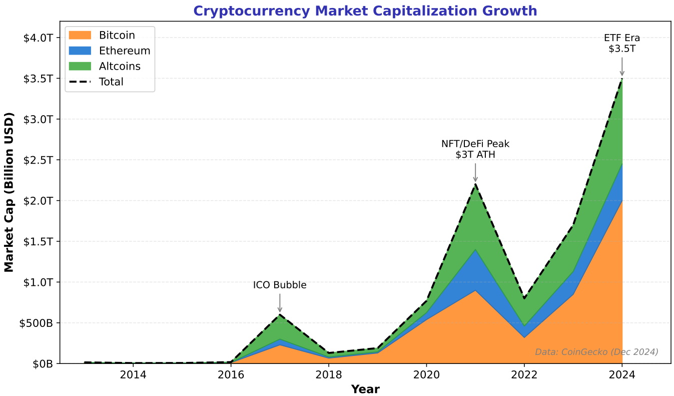
Network Security: Hash Rate Growth



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

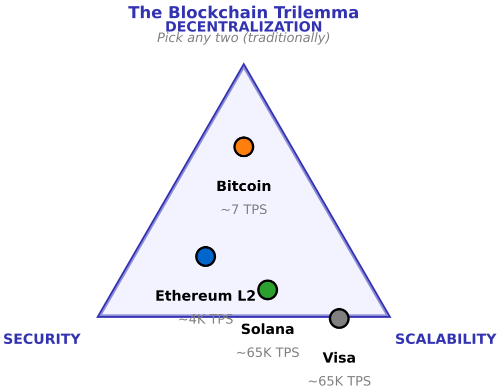
Higher hash rate = more computational cost to attack the network

Market Growth: Cryptocurrency Capitalization



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

Market cap growth reflects institutional adoption and mainstream acceptance



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:

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

Most enterprise "blockchain" projects could use a replicated database

Key Takeaways

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

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

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