Lesson 16: Proof of Work

Module 2: Blockchain Fundamentals

Digital Finance

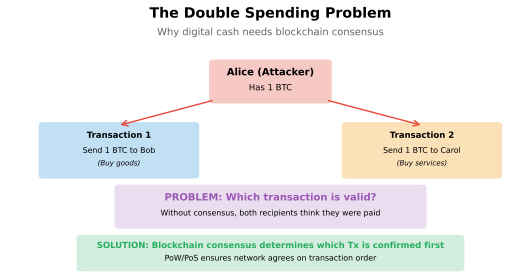
The Double-Spending Problem

Digital Money Challenge:

- Digital files are copyable
- How to prevent spending same coin twice?
- Traditional solution: Central authority (bank)

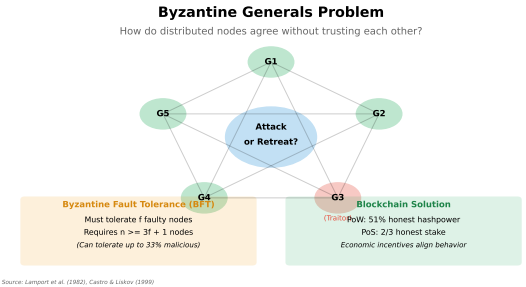
Decentralized Challenge:

- No central ledger
- Network latency
- Conflicting transactions
- Malicious actors



Source: Protocol documentation and distributed systems research

Consensus Problem: Agreeing on Transaction Order



Key Questions:

- Which transaction came first?
- Who decides the canonical order?
- How to prevent censorship or manipulation?
- How to incentivize honest behavior?

Key insight: consensus problem: agreeing continues to evolve with technology advances.

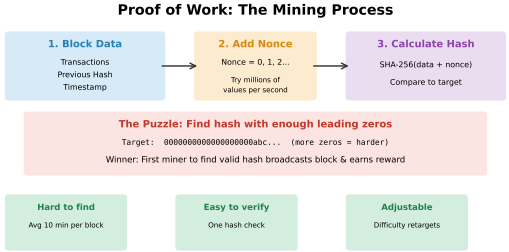
Proof of Work: The Solution

Core Idea:

- Make block creation expensive
- Require computational work
- Probability-based selection
- Longest chain wins

Properties:

- Sybil resistance (one CPU = one vote)
- Objective chain selection rule
- Economic security
- No coordination needed



Source: bitcoin.org (Whitepaper Section 4)

Proof-of-Work provides security through computational cost but has energy concerns.

Hash Puzzle: Finding the Nonce

Mining Goal: Find nonce such that block hash is below target

$$\text{SHA256}(\text{Block Header}) < \text{Target}$$

Block Header Contains:

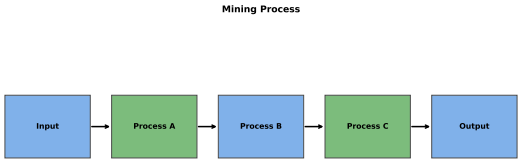
- Previous block hash
- Merkle root (transaction summary)
- Timestamp
- Difficulty target
- Nonce (number to vary)

Example:

Target:	$0000000000000000000f1a2b3c4d\ldots$
Hash attempt 1:	$8a3f2e1d9c\ldots$ (too high)
Hash attempt 2:	$00000000000000000000a1b2c3d\ldots$ (success!)

Understanding hash puzzle: finding is essential for modern financial systems. [Source: Cambridge Bitcoin Electricity Index 2024]

Mining Process Visualization



Steps:

1. Collect transactions from mempool
2. Build Merkle tree, create block header
3. Try different nonces (brute force search)
4. Hash until target reached
5. Broadcast valid block to network

Understanding the process flow is key to identifying optimization opportunities.

Difficulty Target: Controlling Block Time

Target Representation:

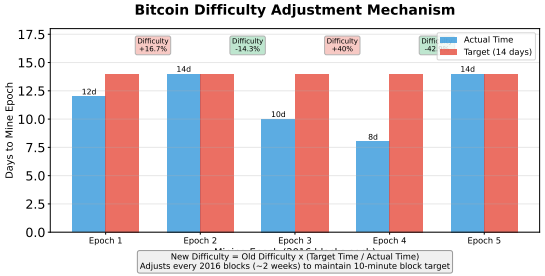
$$\text{Target} = \text{coefficient} \times 2^{8(\text{exponent}-3)}$$

Difficulty:

$$\text{Difficulty} = \frac{\text{Max Target}}{\text{Current Target}}$$

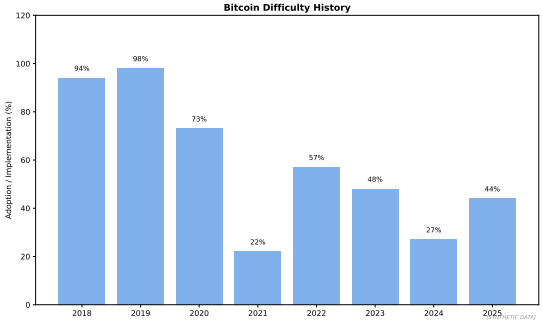
Bitcoin:

- Target block time: 10 minutes
- Adjusts every 2016 blocks (2 weeks)
- Difficulty $\propto$ total hashrate



Source: Protocol documentation and distributed systems research

Difficulty Over Time: Bitcoin Example



Observations:

- Exponential growth from 2009 to 2024
- Difficulty in 2024: $\sim 10^{13}$ times harder than 2009
- Hashrate: From CPU mining to specialized ASICs

Case studies provide concrete evidence of technology impact and adoption patterns. [Source: Blockchain.com, CoinMetrics 2024]

Mining Probability and Expected Time

Probability of Success per Hash:

$$P(\text{success}) = \frac{\text{Target}}{2^{256}}$$

Expected Number of Hashes:

$$E[\text{hashes}] = \frac{2^{256}}{\text{Target}} = \text{Difficulty} \times 2^{32}$$

Expected Time to Find Block:

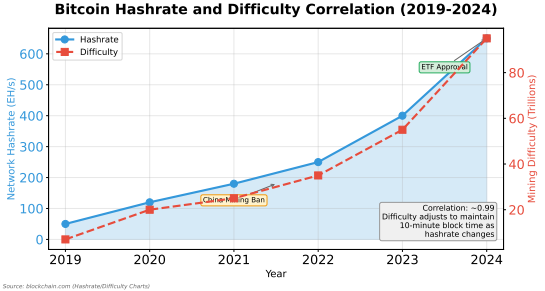
$$T = \frac{\text{Difficulty} \times 2^{32}}{\text{Hashrate}}$$

Example: Difficulty $= 50$ trillion, Hashrate $= 100$ TH/s

$$T = \frac{50 \times 10^{12} \times 2^{32}}{100 \times 10^{12}} \approx 2147 \text{ seconds} \approx 36 \text{ minutes}$$

Source: Protocol documentation and distributed systems research

Mining Difficulty vs Hashrate



Relationship:

- Hashrate increases → blocks found faster
- Difficulty adjusts upward → restores 10-min average
- Self-regulating system maintains predictable issuance

Source: Cryptographic standards (NIST); Computer security textbooks

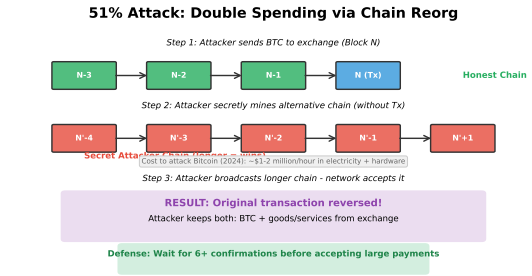
Blockchain Security: The 51% Attack

Attack Scenario:

- Attacker controls >50% hashrate
- Can create longest chain
- Rewrite transaction history
- Double-spend attack

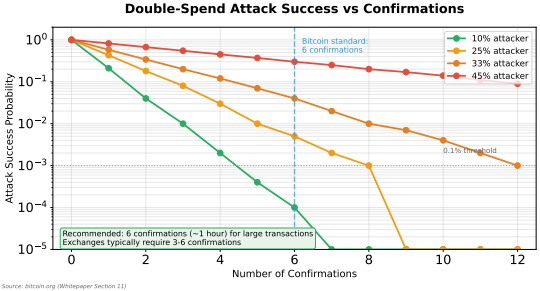
Limitations:

- Cannot steal others' coins
- Cannot create coins from nothing
- Cannot change protocol rules



Security analysis identifies vulnerabilities and helps design robust systems.

Confirmation Depth: Security Over Time



Probability of Reversal:

$$P(\text{reorg after } z \text{ blocks}) \approx \left(\frac{q}{p}\right)^z$$

where p = honest hashrate fraction, q = attacker hashrate fraction

Bitcoin Standard: 6 confirmations ($\sim$1 hour) for high-value transactions

Security analysis identifies vulnerabilities and helps design robust systems.

Mining Economics: Costs and Rewards

Revenue:

- Block reward: 3.125 BTC (as of 2024, halves every 4 years)
- Transaction fees: Variable (0.1–2 BTC per block)

Costs:

- Hardware (ASICs): \$3,000–\$15,000 per unit
- Electricity: 3–6 cents per kWh (industrial rates)
- Cooling, maintenance, facility

Profitability Equation:

$$\text{Profit} = (\text{Block Reward} + \text{Fees}) \times \text{BTC Price} - \text{Electricity Cost}$$

Break-even: Electricity cost $\approx$ 40–60% of revenue at scale

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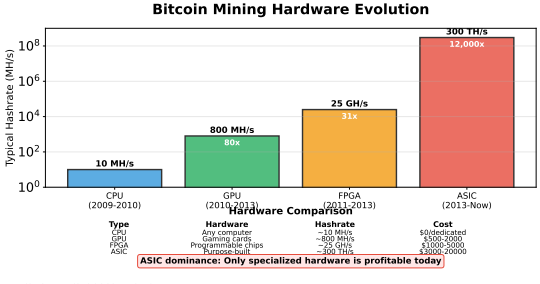
Source: Protocol documentation and distributed systems research

Mining Hardware Evolution



- **2009–2010:** CPU mining (1–10 MH/s)
- **2010–2012:** GPU mining (100–500 MH/s) S21 Hyd: 335 TH/s, S21 XP: 270 TH/s (2024-2025)[1]
- **Modern ASICs:** Antminer S19 Pro (110 TH/s, 3250W)

Understanding history helps predict future developments in the technology. [Source: Cambridge Bitcoin Electricity Index 2024]

[1] Source: `https://www.bitmain.com`

Energy Consumption: The Elephant in the Room

Bitcoin Network (2024):
~1,000-1,050 EH/s (Dec 2025)[a]

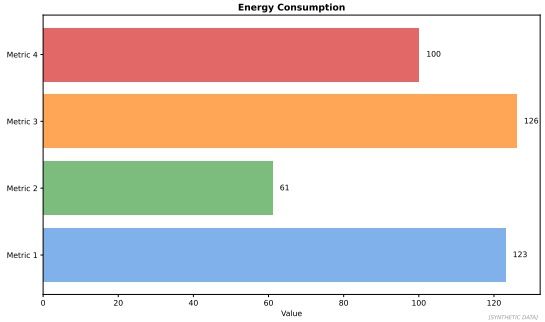
- Power consumption: ~150 TWh/year
- Comparable to Argentina or Netherlands

Per Transaction:
1,179-1,444 kWh (2025)[b]

- vs Visa: ~0.001 kWh
- But: Bitcoin = settlement layer

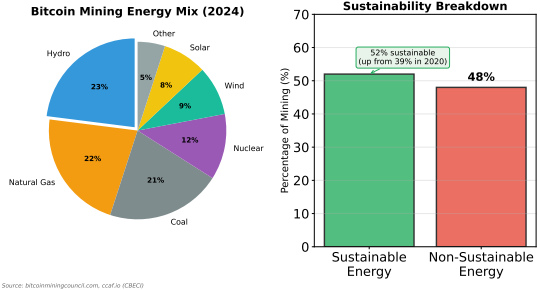
[a] Source: `https://www.coinwarz.com/mining/bitcoin/hashrate-chart`

[b] Source: `https://digiconomist.net/bitcoin-energy-consumption`



Source: Protocol documentation and distributed systems research

Energy Sources: Renewable Debate



Estimates (2024):

- Renewable energy: 40–60% (hydroelectric, wind, solar)
- Natural gas: 20–30%
- Coal: 10–20%
- Nuclear: 5–10%

Trend: Miners seek cheap, stranded renewable energy (e.g., flare gas, curtailed hydro)

Source: Protocol documentation and distributed systems research

Environmental Criticisms and Counterarguments

Criticisms:

- Massive carbon footprint
- E-waste from obsolete ASICs
- Inefficient compared to databases
- Competes with useful computing

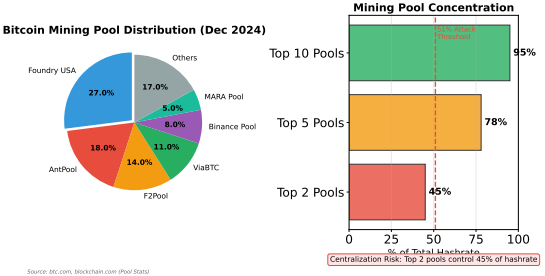
Counterarguments:

- Energy = security (makes attacks expensive)
- Incentivizes renewable buildout
- Banking system also energy-intensive
- Enables censorship-resistant money

Trade-off: Security vs energy efficiency (Proof of Stake addresses this)

Source: Protocol documentation and distributed systems research

Mining Centralization Risks



Concerns:

- Top 5 pools control >70% hashrate
- Geographic concentration (China historically dominant, now US/Kazakhstan)
- Pool operators could censor transactions

Mitigation: Miners can switch pools, Stratum V2 protocol improves decentralization

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Risk management is essential for financial stability and profitability.

Selfish Mining Attack

Strategy:

1. Miner finds block, keeps secret
2. Continues mining on private chain
3. Reveals when ahead by 2+ blocks
4. Honest chain orphaned

Result:

- Unfair revenue (more than hashrate share)
- Effective with $>25\%$ hashrate
- Wastes other miners' work

Security analysis identifies vulnerabilities and helps design robust systems.

Alternatives to Proof of Work

Mechanism	Selection	Pros	Cons
Proof of Work	Computational power	Proven security	Energy intensive
Proof of Stake	Staked capital	Energy efficient	Rich get richer
Proof of Authority	Approved validators	Fast, low energy	Centralized
Proof of Space	Disk storage	Lower energy	Unproven security

Note: Ethereum switched from PoW to PoS in 2022 (The Merge)

Proof-of-Work provides security through computational cost but has energy concerns.

Proof Of Work: Key Takeaways

- **Double-Spending Problem:** Solved by probabilistic consensus via PoW
- **Mining:** Find nonce making block hash $<$ target (SHA256 puzzle)
- **Difficulty:** Auto-adjusts to maintain constant block time (10 min for Bitcoin)
- **Security:** 51% attack possible but expensive; confirmation depth increases safety
- **Economics:** Revenue (block reward + fees) vs costs (hardware + electricity)
- **Energy Debate:** $\sim$150 TWh/year, trade-off between security and efficiency

Next Lesson: Proof of Stake – energy-efficient alternative consensus