THE GRAINGER COLLEGE OF ENGINEERING

CS 521

Technological Foundations of Blockchain and Cryptocurrency

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Topic 3 – Bitcoin

Early Cryptographic Digital Currencies … All Failed

- DigiCash (David Chaum) - 1989
- Mondex (National Westminster Bank) - 1993
- CyberCash (Lynch, Melton, Crocker & Wilson) - 1994
- E-gold (Gold & Silver Reserve) - 1996
- Hashcash (Adam Back) - 1997
- Bit Gold (Nick Szabo) - 1998
- B-Money (Wei Dai) - 1998
- Lucre (Ben Laurie) - 1999

Why did Early Digital Currencies Fail?

- Merchant adoption
- Centralization
- Double spending
- Consensus

Double Spend attack

- A simple attack:
  - When one person can use the same coin multiple times to buy things
- Easily solved with a centralized system
- Much harder when decentralized

The Riddle Remained

How to move value peer-to-peer
without any trusted central intermediary

Bitcoin: A Peer-to-Peer Electronic Cash System

From: Satoshi Nakamoto <satoshi <at> vistomail.com>

Subject: Bitcoin P2P e-cash paper

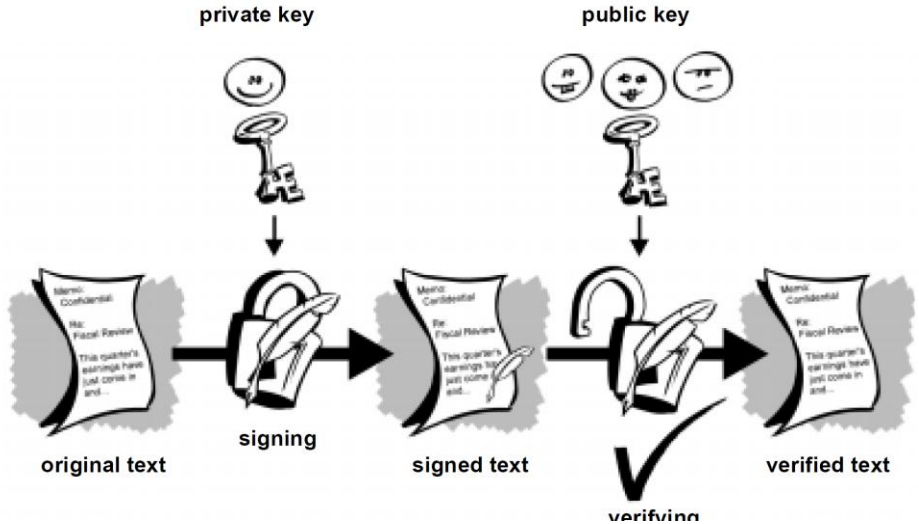
Newsgroups: gmane.comp.encryption.general

Date: Friday 31st October 2008 18:10:00 UTC

I've been working on a new electronic cash system that's fully peer-to-peer, with no trusted third party.

Bitcoin's Goal

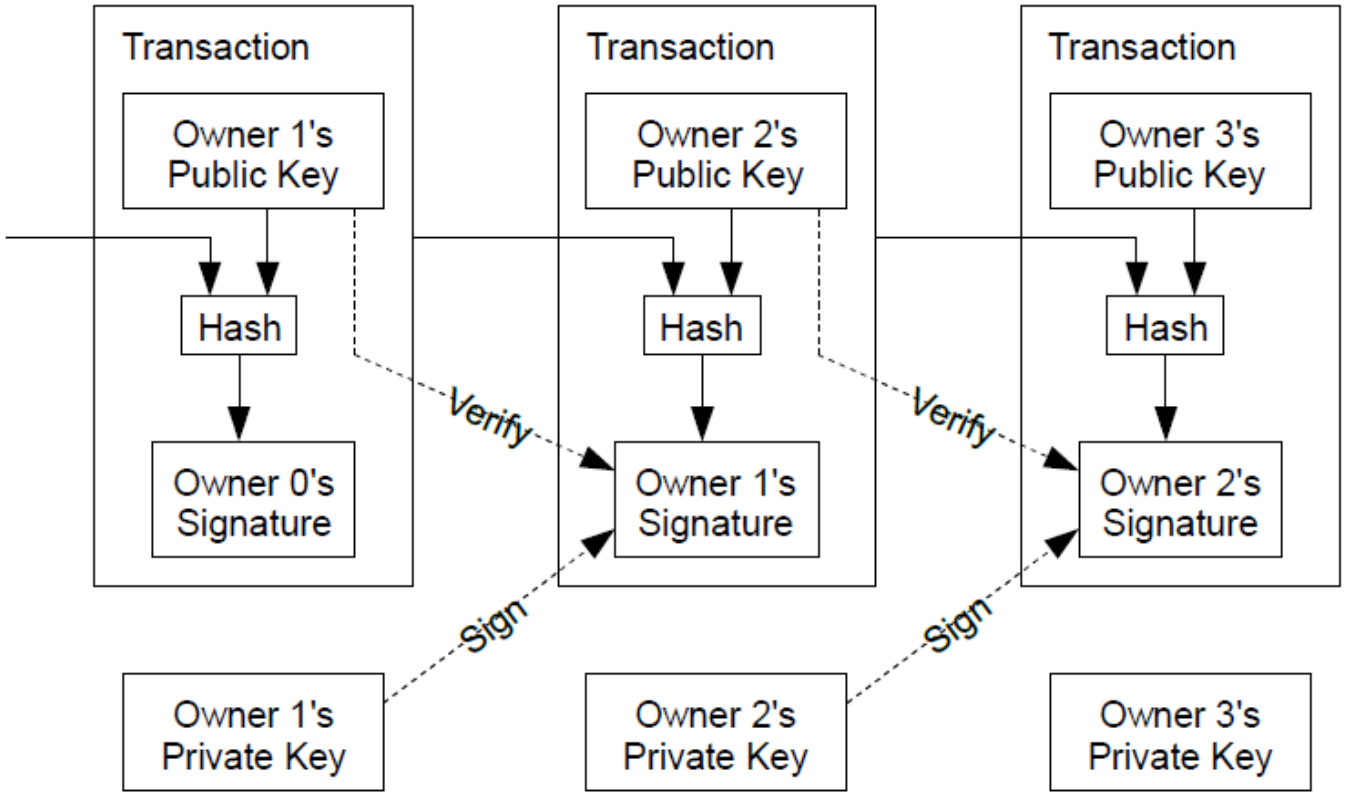
- Peer-to-peer digital money
  - No intermediaries (banks, centralized parties)
- Digital signatures were clearly the right direction



  - But the double-spending riddle could not be solved
  - Centralized / intermediary can solve double-spending, but defies the purpose

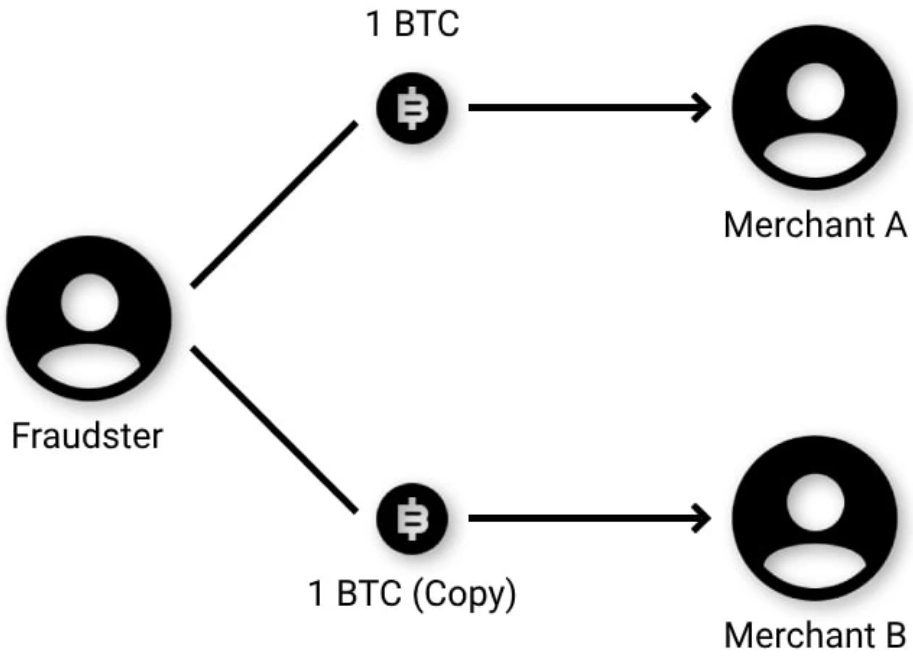
Coins and Transactions

- Coins and transfers
  - Coin: chain of digital signatures (hash pointer list data-structure)
  - Transfer C from A to B: C' = sign(A, hash(C,B))



Double Spending

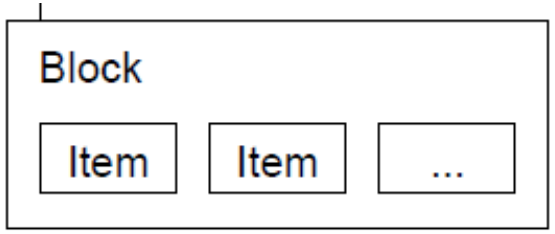
So far nothing to stop a fraudster to send the same coin to two parties

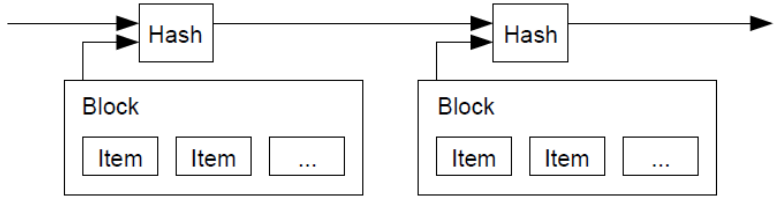


Solution: enforce with a very high probability, a total order on transactions

Timestamp Servers: Blocks and Total Orders

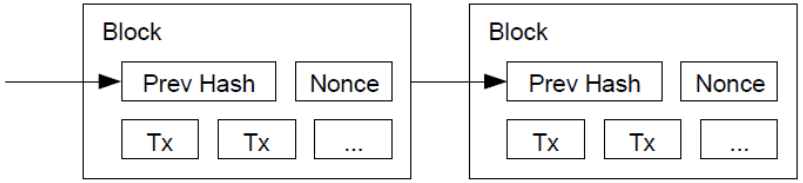
- Put each transaction in a totally-ordered block of transactions
  - This is the only way transactions get communicated
- Linked list of hash pointers to enforce total order on blocks
- Problem of divergence remains, but lifted from transactions to blocks
- Need to enforce total order on blocks; in a decentralized way





Proof-of-Work

- Idea
  - Have only one block proposer at a time, but who?
  - Whoever solves a puzzle generation challenge first (recall previous lecture)
    - Requires computational power, so solving it is … proof of work



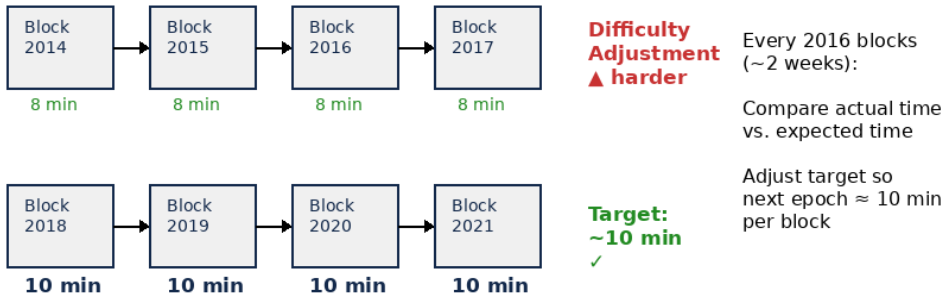
- Specifically, the puzzle challenge is to find Nonce in the block such that the hash of the block is smaller than an epsilon (hash starting with zeros)
- Easy to verify that such Nonce is indeed correct, so all nodes update chain
- Problem of divergence still exists in theory; but nodes pick longest chain

Decentralized Network

- Nodes can join and leave. They all execute the same protocol:
  - 1. New transactions are broadcast to all nodes.
  - 2. Each node collects new transactions into a block.
  - 3. Each node works on finding a difficult proof-of-work for its block.
  - 4. When a node finds a proof-of-work, it broadcasts the block to all nodes.
  - 5. Nodes accept the block only if all transactions in it are valid and not already spent.
  - 6. Nodes express their acceptance of the block by working on creating the next block in the chain, using the hash of the accepted block as the previous hash.
- Nodes always consider the longest chain
- Economic incentive:
  - First transaction in the block is a new coin owned by the block creator/proposer/miner

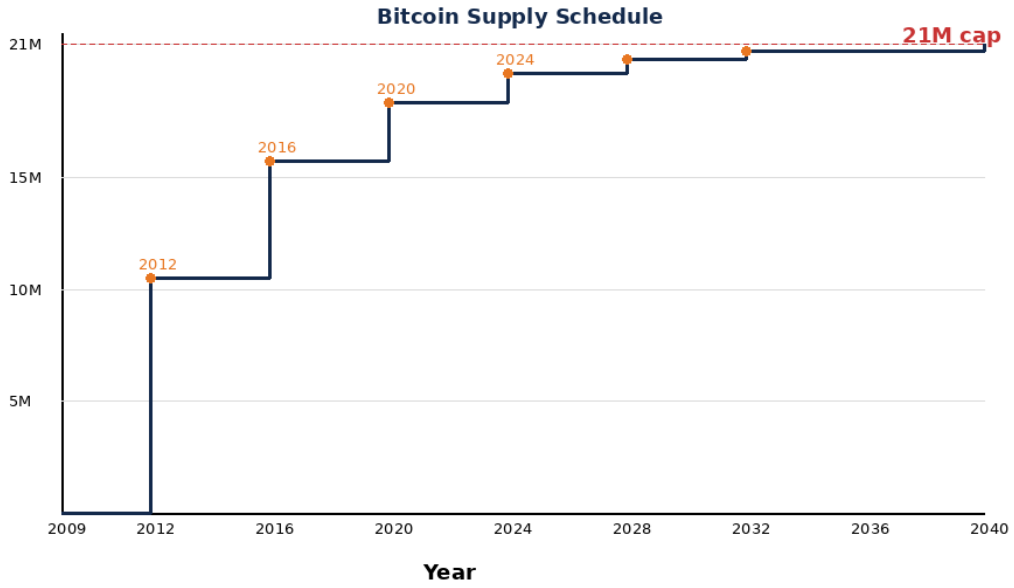
Mining Economics: Difficulty Adjustment

- Target: one block every ~10 minutes
  - Too fast? Mining is too easy. Too slow? Network unusable
- Difficulty adjusts every 2016 blocks (~2 weeks)
  - Compare actual time vs. expected time (2016 × 10 min)
  - If blocks came too fast → increase difficulty (smaller target)
  - If blocks came too slow → decrease difficulty (larger target)
- Self-regulating feedback loop
  - Works regardless of total hash power in the network



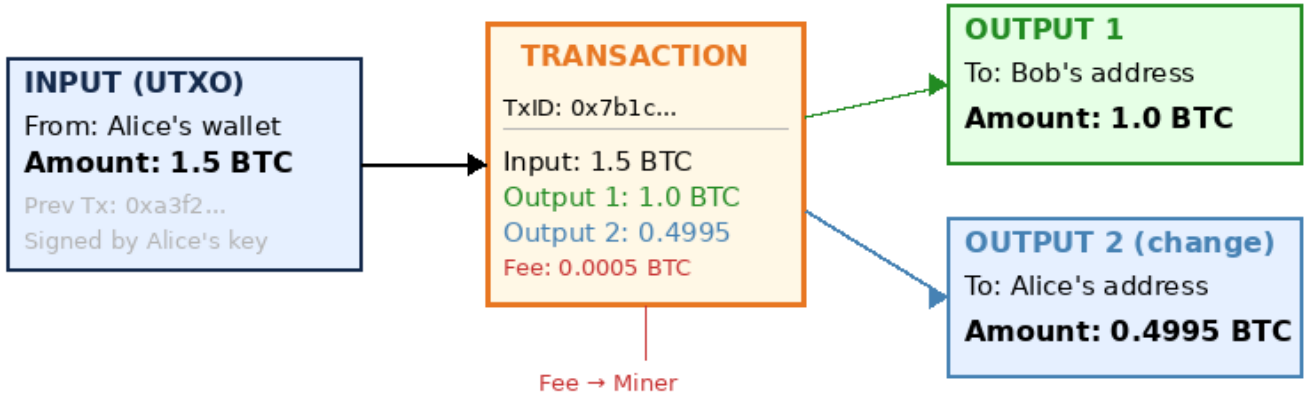
Bitcoin Supply and Halving

- Fixed supply cap: 21 million BTC
- Block reward halves every 210,000 blocks (~4 years)
  - 2009: 50 BTC → 2012: 25 → 2016: 12.5 → 2020: 6.25 → 2024: 3.125
- Last bitcoin mined around year ~2140
- Deflationary by design
  - After all BTC mined, miners earn only transaction fees
- Contrast with fiat: central banks can print unlimited money



A Concrete Transaction: The UTXO Model

- Bitcoin does not use account balances – it uses Unspent Transaction Outputs (UTXOs)
  - Like paying with bills: you hand over a $20, get change back

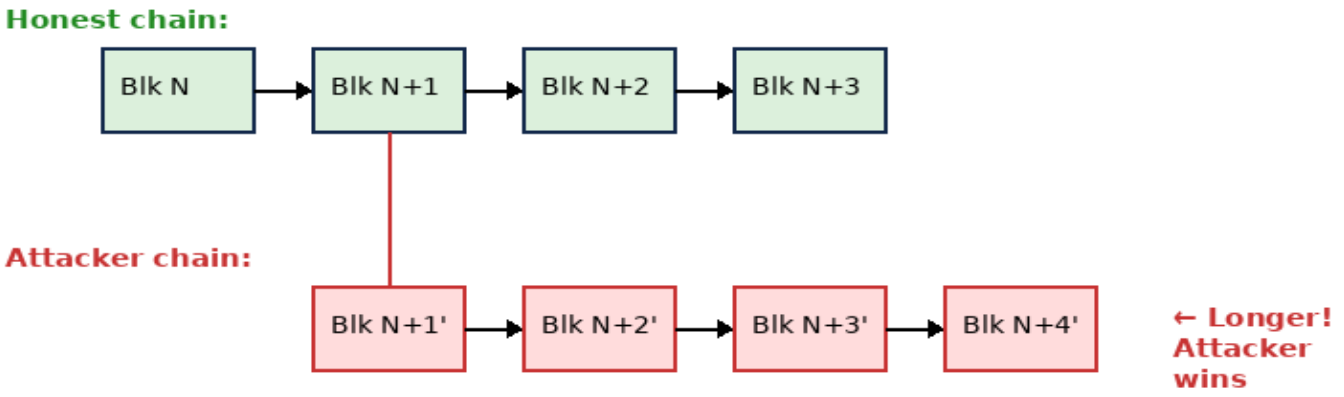


UTXO Model (Unspent Transaction Output)

- Coins are not accounts with balances — they are unspent outputs from previous transactions
- To spend, you consume entire UTXOs as inputs and create new UTXOs as outputs
- Change goes back to yourself as a new UTXO (like getting change from a $20 bill)
- Transaction fee = sum(inputs) – sum(outputs) — goes to the miner who includes the tx

Security: The 51% Attack

- What if an attacker controls >50% of the network hash power?
  - Can build a longer chain, rewriting history and reversing transactions
- Defense: wait for multiple confirmations before trusting a transaction



With >50% hash power, attacker can build a longer chain, reversing confirmed transactions

At 10% hash power: 0.02% chance to reverse 6 confirmations | At 30%: 17.7% | At 50%+: certain

This is why merchants wait for multiple confirmations (typically 6 blocks ≈ 1 hour)

Genesis Block and Bitcoin Milestones

- Satoshi Nakamoto mined the first block on January 3, 2009
- The coinbase parameter contained a message that became legendary:

The Times
03/Jan/2009
Chancellor on brink of second bailout for banks

Genesis Block (Block #0)

Hash: 000000000019d6689c085ae165831e934ff763ae46a2a6c172b3f1b60a8ce26f

Timestamp: 2009-01-03 18:15:05 UTC

Coinbase: "The Times 03/Jan/2009 Chancellor on brink of second bailout for banks"

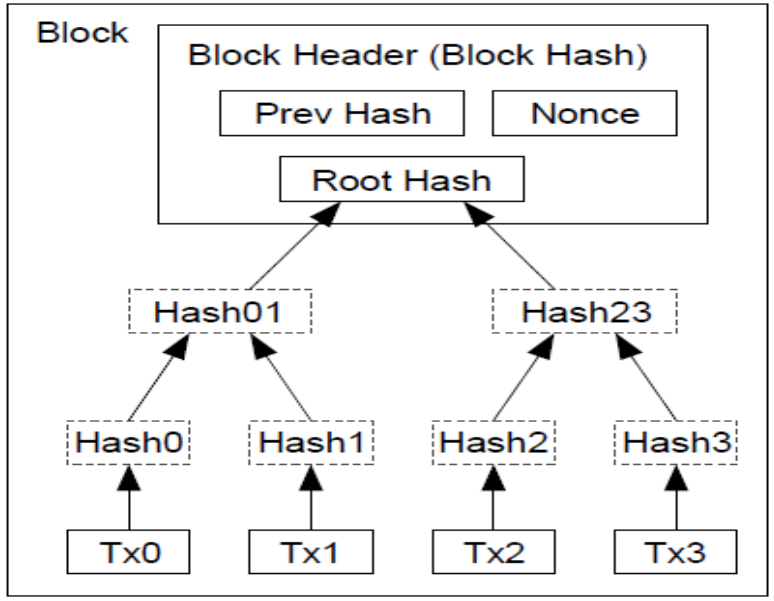
Reward: 50 BTC (unspendable — hardcoded special case)

Bitcoin Milestones

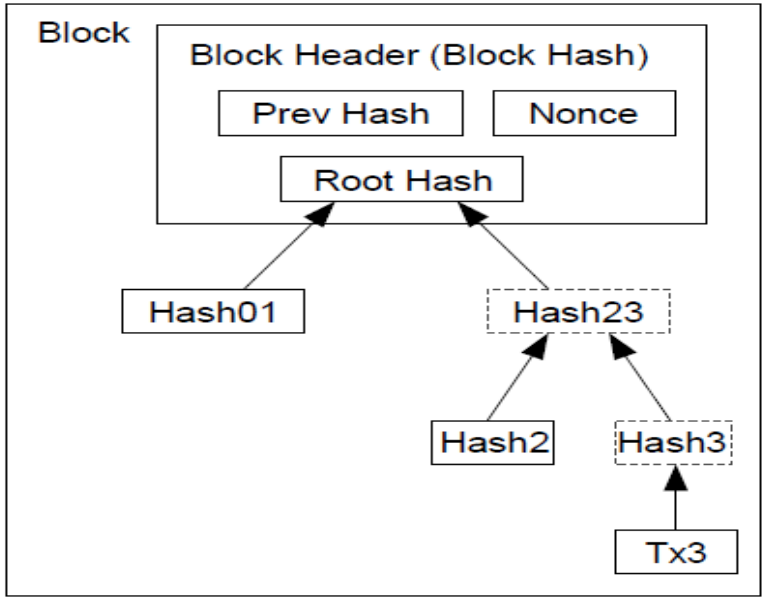
- May 22, 2010: Laszlo Hanyecz pays 10,000 BTC for two pizzas (~$41 at the time)
- First known Bitcoin price: $0.0009 (Oct 2009, New Liberty Standard)
- Satoshi Nakamoto's identity remains unknown — last public message: April 2011

Reclaiming Space

- Transactions need not be stored on-chain permanently
- Stored in Merkle tree, whose root hash is in the block header
- Once buried under enough blocks, spent transactions can be pruned
  - Only the Merkle root is needed to verify the block's integrity
  - A block header is only ~80 bytes vs. ~1 MB for a full block



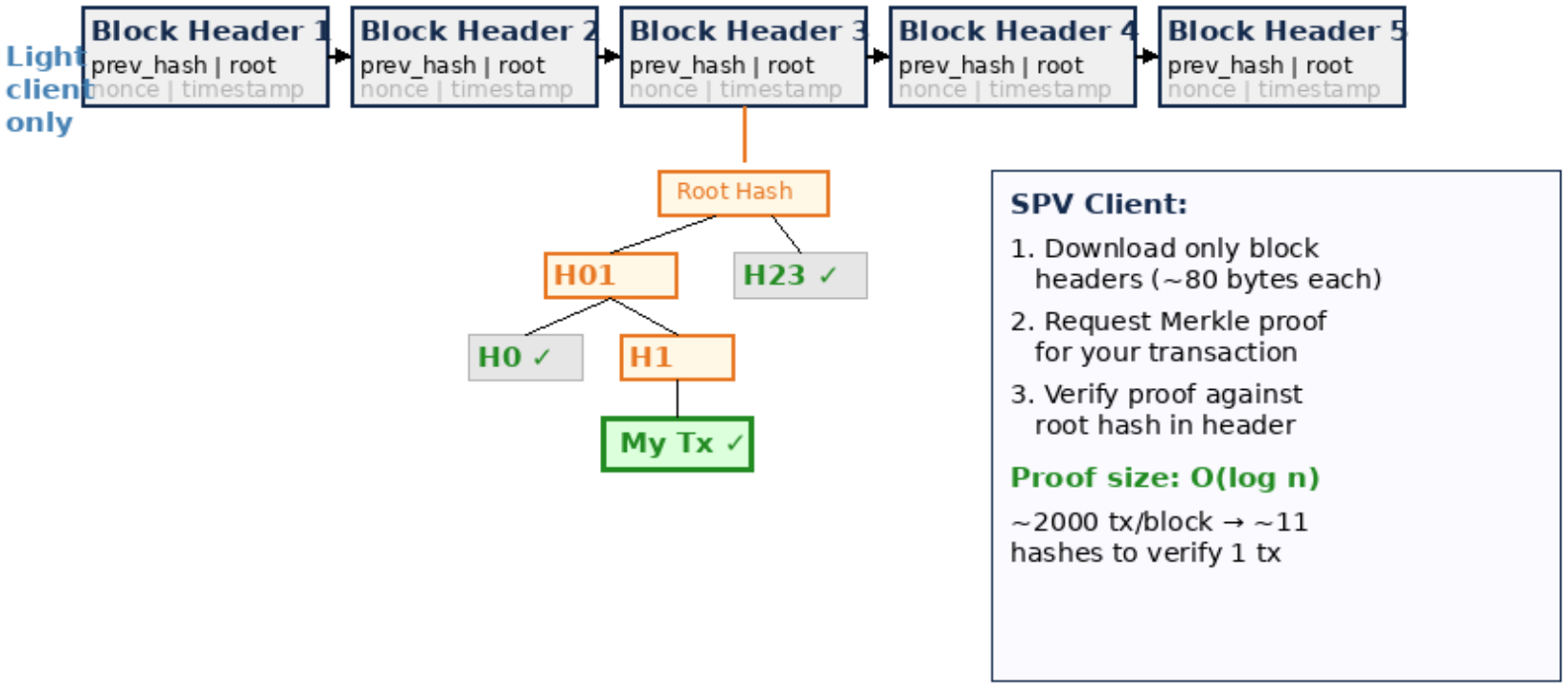
Transactions Hashed in a Merkle Tree



After Pruning Tx0-2 from the Block

Simplified Payment Verification (SPV)

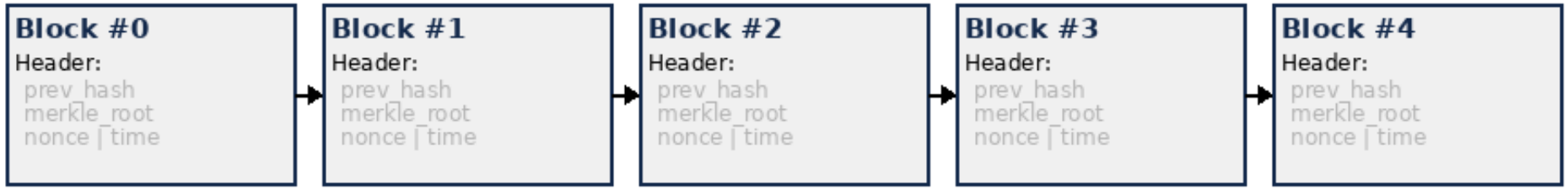
- Lightweight clients verify payments without downloading the full blockchain
  - Download only block headers (~80 bytes each, vs ~1 MB per full block)
  - Request a Merkle proof for the specific transaction from a full node
- Proof size is O(log n) – only ~11 hashes to verify 1 tx among ~2000



How It All Fits Together

- From a signed transaction to an immutable, decentralized ledger:

The Blockchain:



Security Properties

Immutability
Changing old blocks requires redoing all subsequent PoW

Decentralized
No single point of failure; any node can verify

Double-Spend Resistant
Longest chain wins; attacker needs >50% power

Incentive-Aligned
Miners profit from honest behavior (block reward + fees)