Bitcoin and the Blockchain

COS 418/518: Distributed Systems
Lecture 21

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Bitcoin: 10,000 foot view

- New bitcoins are “created” every ~10 min, owned by “miner” (more on this later)
- Thereafter, just keep record of transfers
  - e.g., Alice pays Bob 1 BTC
- Basic protocol:
  - Alice signs transaction: txn = $Sign_{Alice}$ (BTC, PK_{Bob})
  - Alice shows transaction to others…

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Problem: Equivocation!

Can Alice “pay” both Bob and Charlie with same bitcoin ?

(Known as “double spending”)

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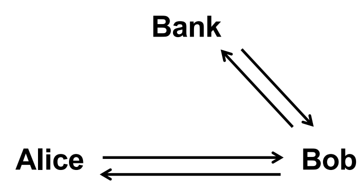
How traditional e-cash handled problem



- When Alice pays Bob with a coin, Bob validates that coin hasn’t been spend with trusted third party
- Introduced “blind signatures” and “zero-knowledge protocols” so bank can’t link withdrawals and deposits

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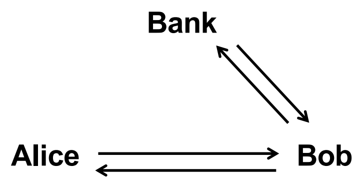
How traditional e-cash handled problem



- When Alice pays Bob with a coin, Bob validates that coin hasn't been spend with trusted third party

Bank maintains linearizable log of transactions

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Problem: Equivocation!

Goal: No double-spending in decentralized environment

Approach: Make transaction log

1. public
2. append-only
3. strongly consistent

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Bitcoin: 10,000 foot view

- Public
  - Transactions are signed: txn = $Sign_{Alice}$ (BTC, PK_{Bob})
  - All transactions are sent to all network participants
- No equivocation: Log append-only and consistent
  - All transactions part of a hash chain
  - Consensus on set/order of operations in hash chain

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Cryptography Hash Functions

- Take message *m* of arbitrary length and produces \fixed-size (short) number *H(m)*
  - *e.g., SHA-1 produces 160-bit output, SHA-256 has 256-bit output*
- One-way function
  - **Efficient:** Easy to compute *H(m)*
  - **Hiding property:** Hard to find an *m*, given *H(m)*
- Collision resistance:
  - **Strong resistance:** Find any m != m' such that H(m) == H(m')
  - **Weak resistance:** Given m, find m' such that H(m) == H(m')

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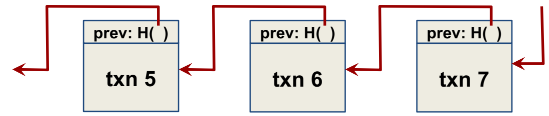
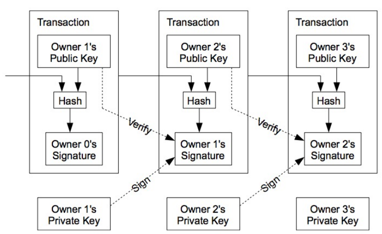
Tamper-evident logging

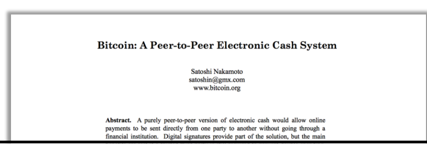
Blockchain: Append-only hash chain



- Hash chain creates “tamper-evident” log of txns
- Security based on collision-resistance of hash function
  - Given m and h = hash(m), difficult to find m’ such that h = hash(m’) and m != m’

Blockchain: Append-only hash chain

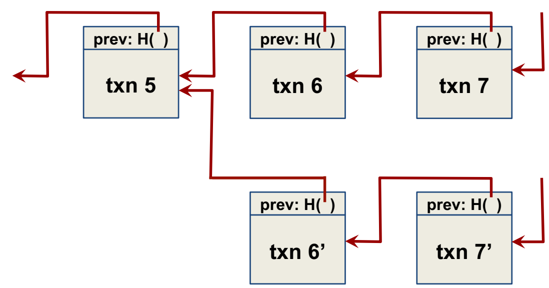



Bitcoin: A Peer-to-Peer Electronic Cash System

Satoshi Nakamoto
satoshin@gmx.com
www.bitcoin.org

Abstract. A purely peer-to-peer version of electronic cash would allow online payments to be sent directly from one party to another without going through a financial institution. Digital signatures provide part of the solution, but the main

Problem remains: forking



Goal: Consensus

- Fault-tolerant protocols to achieve consensus of replicated log with ***malicious*** participants
  – Requires: ***n >= 3f + 1*** nodes, at most ***f*** faulty
- Problem
  – Communication complexity is n^2
  – Requires **strong view** of network participants

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Consensus susceptible to "Sybils"

- Traditional consensus protocols based on membership
  – … assume independent failures …
  – … which implies strong notion of identity
- "Sybil attack" (p2p literature ~2002)
  – Idea: one entity can create many "identities" in system
  – Typical defense: 1 IP address = 1 identity
  – Problem: IP addresses aren't difficult / expensive to get, esp. in world of botnets & cloud services

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Consensus based on "work"

- Rather than "count" IP addresses, bitcoin "counts" the amount of CPU time / electricity that is expended

> **"The system is secure as long as honest nodes collectively control more CPU power than any cooperating group of attacker nodes."**
> **- Satoshi Nakamoto**

- Proof-of-work: Cryptographic "proof" that certain amount of CPU work was performed

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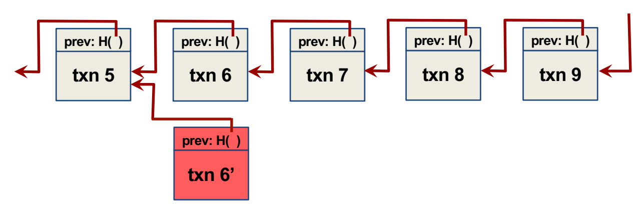
Key idea: Chain length requires work



- Generating a new block requires "proof of work"
- "Correct" nodes accept longest chain
- Creating fork requires rate of malicious work >> rate of correct
  – So, the older the block, the "safer" it is from being deleted

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Use hashing to determine work!

- Recall hash functions are one-way / collision resistant
  – Given *h*, hard to find *m* such that *h* = *hash(m)*
- But what about finding partial collision?
  – *m* whose hash has most significant bit = 0?
  – *m* whose hash has most significant bit = 00?
  – Assuming output is randomly distributed, complexity grows exponentially with # bits to match

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Bitcoin proof of work

Find **nonce** such that

hash (**nonce** || prev_hash || block data) < target

e.g., hash has certain number of leading 0's

What about changes in total system hashing rate?

- Target is recalculated every 2 weeks
- Goal: One new block every 10 minutes

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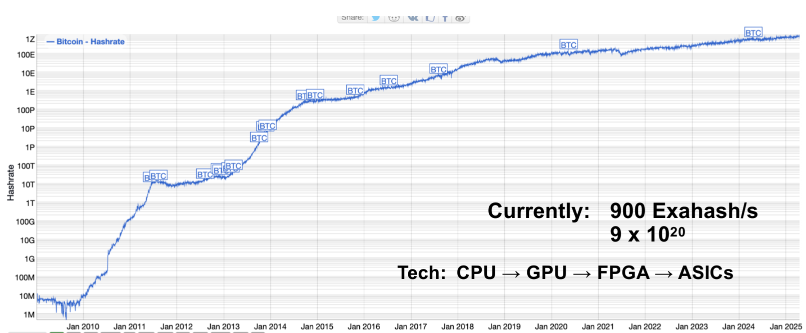
Historical hash rate trends of bitcoin



Currently: 900 Exahash/s
9×10^{20}

Tech: CPU → GPU → FPGA → ASICs

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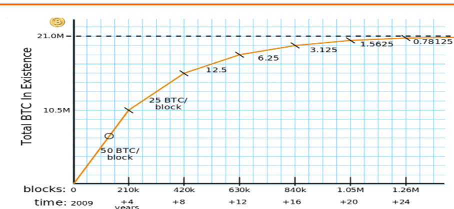
Why consume all this energy?



- Creating a new block creates bitcoin!
  – Initially 50 BTC, decreases over time, currently 3.125
    - Last halving on April 19, 2024
    - Block height is 893,272 as of 4-20-2025
  – New bitcoin assigned to party named in new block, called "mining" as you search for gold/coins

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Bitcoin is worth (LOTS OF) money!

As of April 20, 2025, 3.125 BTC = ~$264,400

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Incentivizing correct behavior?

- Race to find nonce and claim block reward, at which time race starts again for next block

  hash (**nonce** || prev_hash || block data)

  – As solution has prev_hash, corresponds to particular chain

- Correct behavior is to accept longest chain
  – "Length" determined by aggregate work, not # blocks
  – So miners incentivized only to work on longest chain, as otherwise solution not accepted
  – Remember blocks on other forks still "create" bitcoin, but only matters if chain in collective conscious (majority)

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Form of randomized leader election

- Each time a nonce is found:
  – New leader elected for past epoch (~10 min)
  – Leader elected randomly, probability of selection proportional to leader's % of global hashing power
  – Leader decides which transactions comprise block

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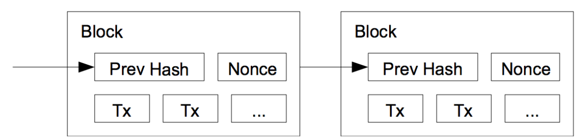
One block = many transactions



- Each miner picks a set of transactions for block
- Builds "block header": prevhash, version, timestamp, txns, …
- Until hash < target OR another node wins:
  – Pick nonce for header, compute hash = SHA256(SHA256(header))

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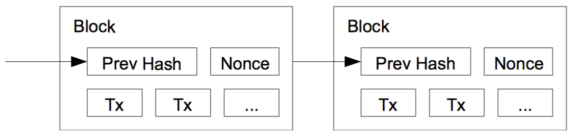
Transactions are delayed



- At some time *T*, block header constructed
- Those transactions had been received *[T – 10 min, T]*
- Block will be generated at time T + 10 min (on average)
- So transactions are from 10 - 20 min before block creation
- Can be much longer if "backlog" of transactions are long

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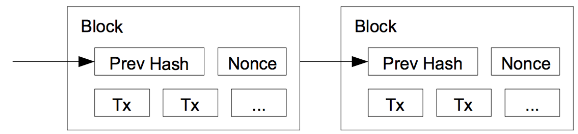
Commitments further delayed



- When do you trust a transaction?
  - After we know it is "stable" on the hash chain
  - Recall that the longer the chain, the hard to "revert"
- Common practice: transaction "committed" when 6 blocks deep
  - i.e., Takes another ~1 hour for txn to become committed

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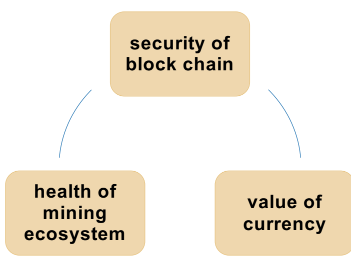
Bitcoin & blockchain intrinsically linked



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Summary

- Coins xfer/split between "addresses" (PK) in txns
- Blockchain: Global ordered, append-only log of txns
  - Reached through decentralized consensus
    - Each epoch, "random" node selected to batch transactions into block and append block to log
  - Nodes incentivized to perform work and act correctly
    - When "solve" block, get block rewards + txn fees
    - Only "keep" reward if block persists on main chain

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Appendix

Transaction format: strawman

Create 12.5 coins, credit to Alice	
Transfer 3 coins from Alice to Bob	SIGNED(Alice)
Transfer 8 coins from Bob to Carol	SIGNED(Bob)
Transfer 1 coins from Carol to Alice	SIGNED(Carol)

How do you determine if Alice has balance?
Scan backwards to time 0 !

Transaction format

Inputs:	Ø *// Coinbase reward*	
Outputs:	25.0→PK_Alice	
Inputs:	*H*(prevtxn, 0) *// 25 BTC from Alice*	
Outputs:	25.0→PK_Bob	SIGNED(Alice)
Inputs:	*H* (prevtxn, 0) *// 25 BTC From Alice*	
Outputs:	5.0→PK_Bob, 20.0 →PK_Alice2	SIGNED(Alice)
Inputs:	*H* (prevtxn1, 1), *H*(prevtxn2, 0) // 10+5 BTC	
Outputs:	14.9→PK_Bob	SIGNED(Alice)

- Transaction typically has 1+ inputs, 1+ outputs
- Making change: 1st output payee, 2nd output self
- Output can appear in single later input (avoids scan back)

Transaction format

Inputs:	Ø *// Coinbase reward*	
Outputs:	25.0→PK_Alice	
Inputs:	*H*(prevtxn, 0) *// 25 BTC from Alice*	
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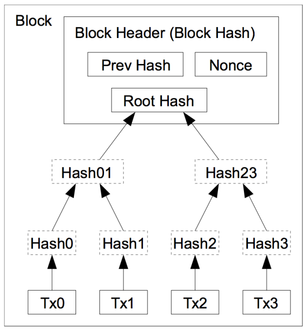
Inputs:	*H* (prevtxn1, 1), *H*(prevtxn2, 0) // 10+5 BTC	
Outputs:	14.9→PK_Bob	SIGNED(Alice)

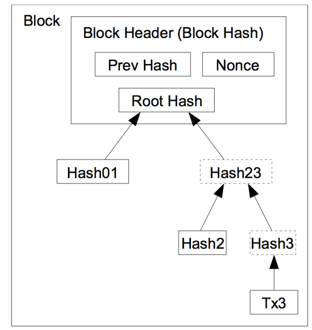
- Unspent portion of inputs is “transaction fee” to miner
- In fact, “outputs” are stack-based scripts
- 1 Block = 1MB max

Storage / verification efficiency



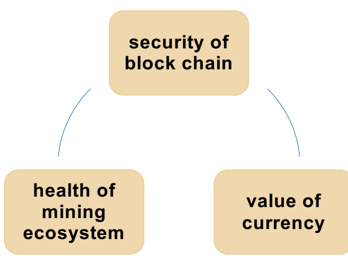
- Merkle tree
  - Binary tree of hashes
  - Root hash “binds” leaves given collision resistance
- Using a root hash
  - Block header now constant size for hashing
  - Can prune tree to reduce storage needs over time

Storage / verification efficiency



- Merkle tree
  - Binary tree of hashes
  - Root hash “binds” leaves given collision resistance
- Using a root hash
  - Block header now constant size for hashing
  - Can prune tree to reduce storage needs over time
    - Can prune when all txn outputs are spent
    - Now: 80GB pruned, 300GB unpruned

Bitcoin & blockchain intrinsically linked



Rich ecosystem: Mining pools

- Mining == gambling:
  - Electricity costs $, huge payout, low probability of winning
- Development of mining pools to ***amortize risk***
  - Pool computational resources, participants “paid” to mine e.g., rewards “split” as a fraction of work, etc
  - Verification? Demonstrate “easier” proofs of work to admins
  - Prevent theft? Block header (coinbase txn) given by pool

More than just currency…

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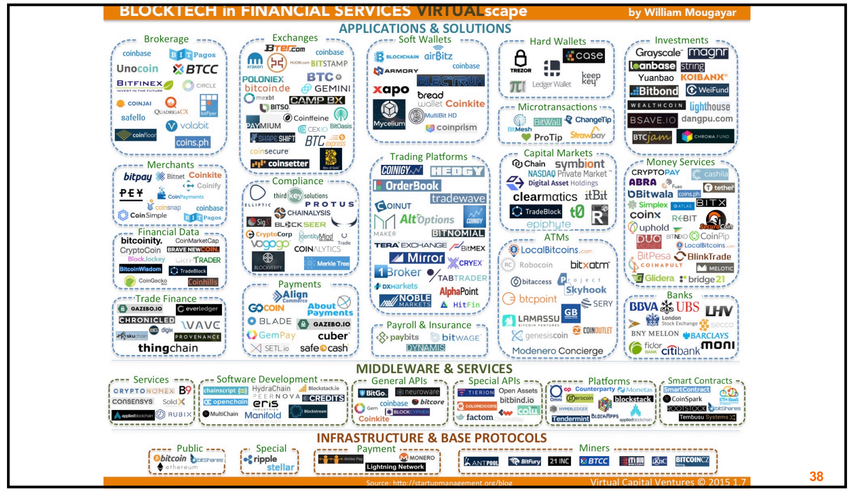

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