Caltech

CS 142: Lecture 10.1
Distributed Ledger and Bitcoin

Richard M. Murray

2 December 2019

Goals:

- Describe how distributed ledgers and blockchains work
- Review the basics of Bitcoin (with emphasis on distributed algorithms)

Reading:

- Bitcoin: A peer-to-peer electronic cash system, Satoshi Nakamoto. http://bitcoin.org/bitcoin.pdf, 2008.
- A. Narayanan, J. Bonneau, E. Felten, A. Miller, S. Goldfeder, *Bitcoin and Cryptocurrency Technologies*. Princeton University Press, 2017. Chapter 1 (optional) and Chapter 2. http://bitcoinbook.cs.princeton.edu
- [optional] J. Garay and A. Kiayias and N. Leonardos, The Bitcoin Backbone Protocol: Analysis and Applications, Cryptology ePrint Archive, Report 2014/765, https://eprint.iacr.org/2014/765 (revised 1 Jul 2019)

Distributed Databases versus Distributed Ledger

Centralized relational databases

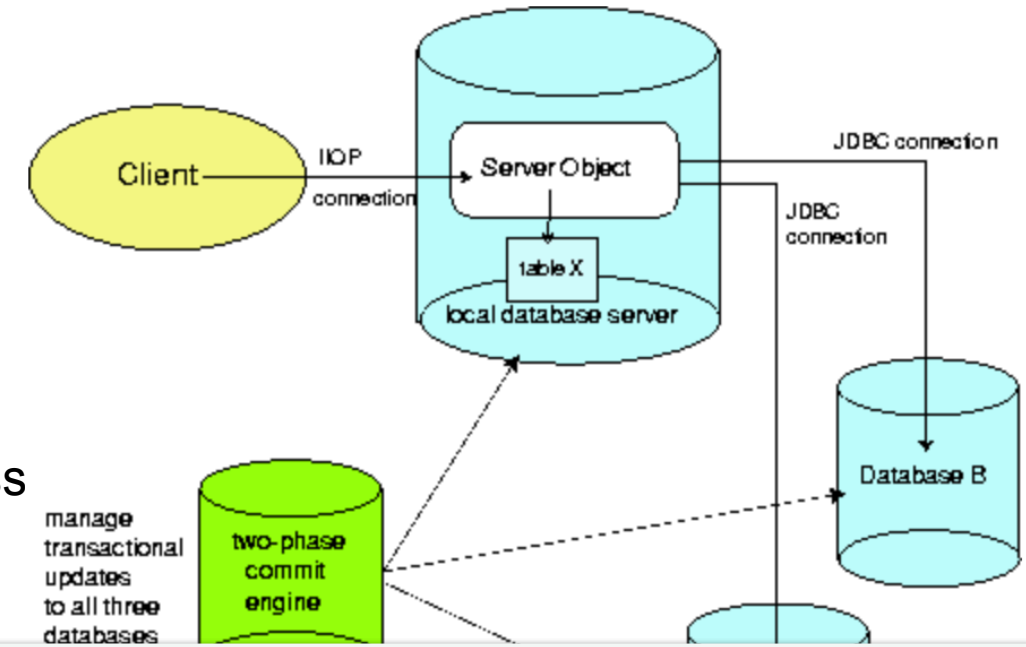
- (Multiple) clients talk to central server
- Server manages competing requests, assigns priority, prevents conflicts
- Examples: web server

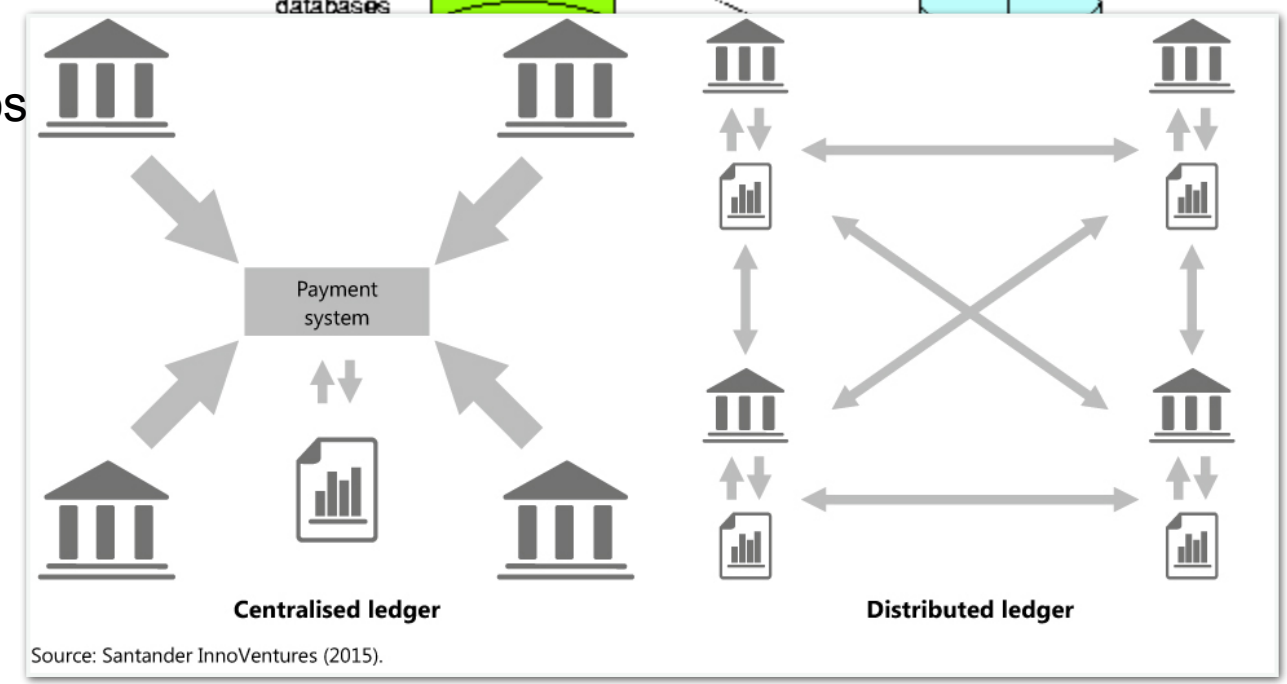
Distributed databases

- Distribute storage of information across multiple locations
- Distributed consensus algorithm is used to ensure consistency
- Examples: 2PC, 3PC, Paxos

Distributed *ledgers*

- Adds additional features
  - Complete (unalterable) history of transactions
  - Protection against (Byzantine) attack

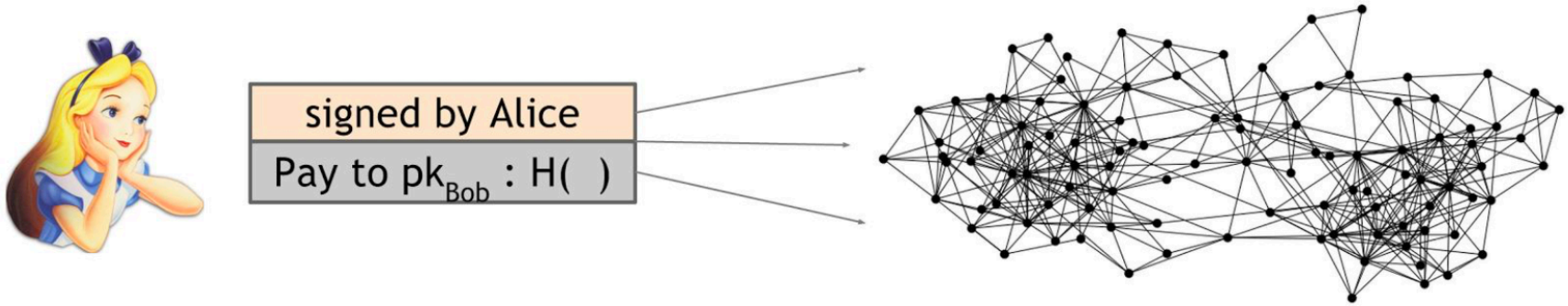




Source: Santander InnoVentures (2015).

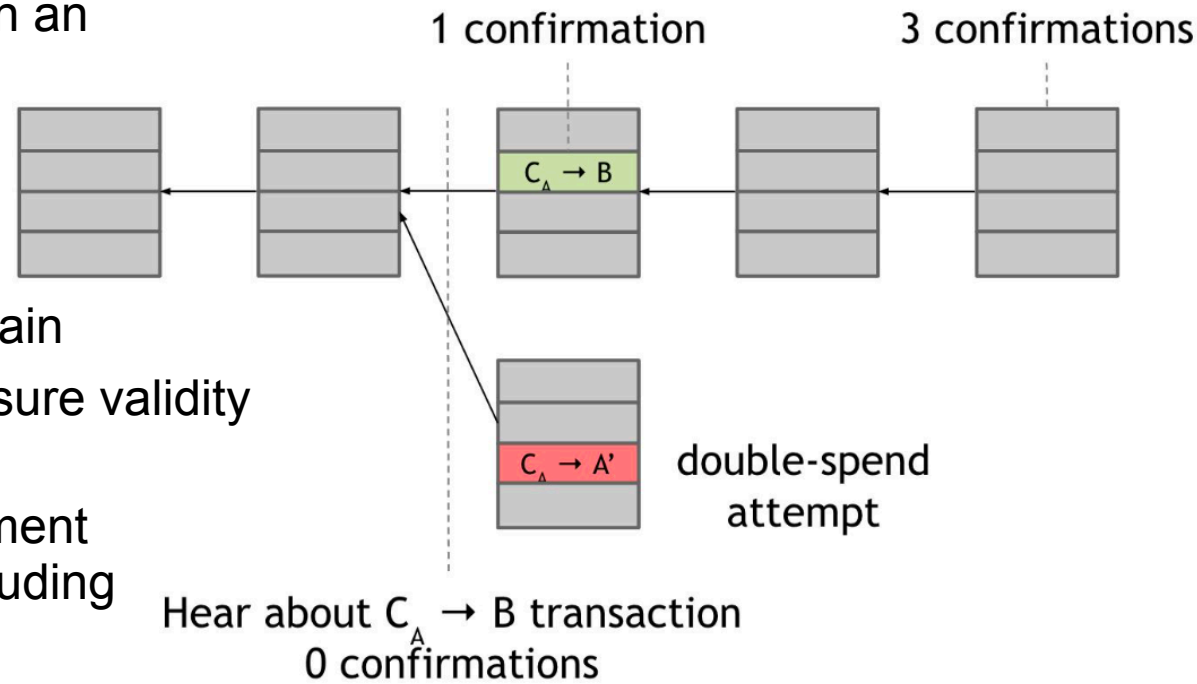
Example: Bitcoin

Bitcoin = mechanism for maintaining a distributed ledger of payment transactions



Operation of the bitcoin network

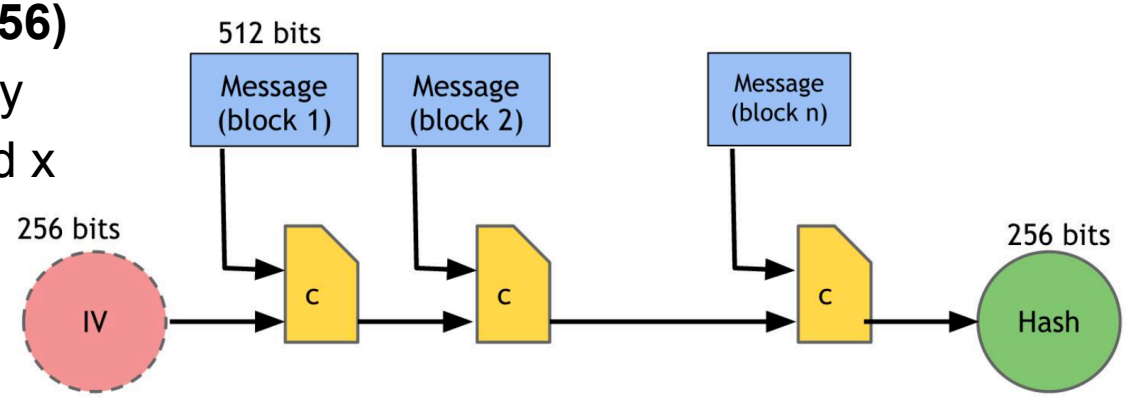
- Transactions requests are collected by "miners" (acceptors) and bundled into blocks
- Blocks are added to the ledger in an append-only chain (blockchain)
- Miners run a consensus protocol to agree on the blockchain
- Miners are paid for the effort required to maintain the blockchain
- Digital signatures are used to insure validity of all transactions and blocks
- "Proof of work" is used to implement consensus and break "ties" (including "double spend" attacks)



Encryption Technologies

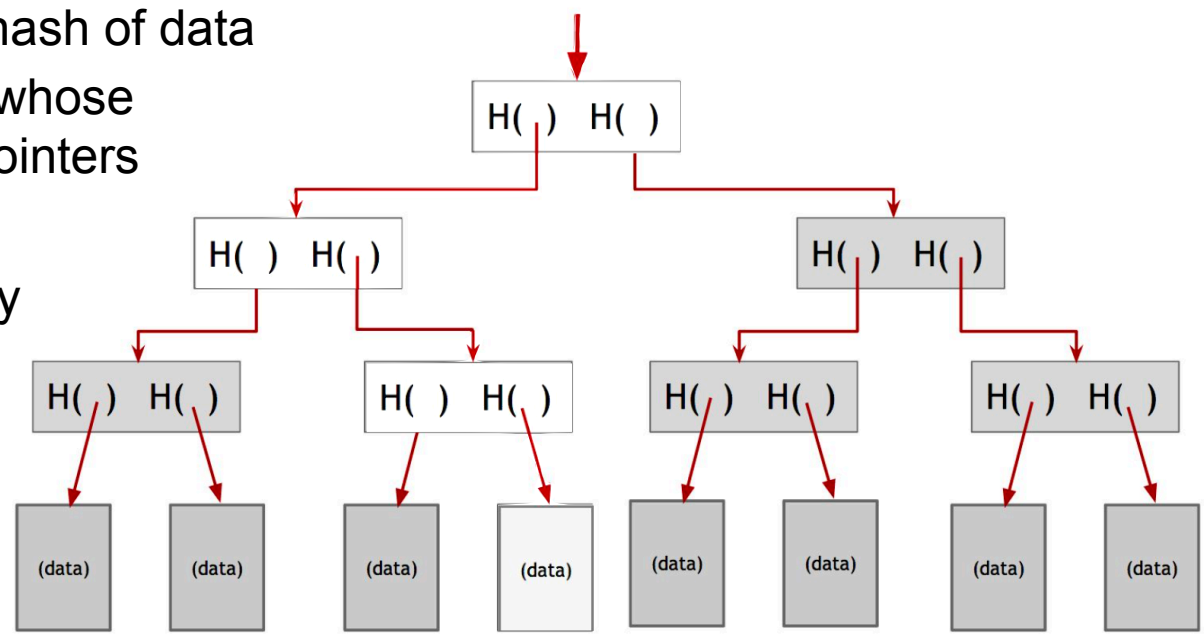
Cryptographic hash functions (SHA256)

- Collision resistant: H(x) ≠ H(y) if x ≠ y
- Hiding: given H(nonce || x), can't find x
- Puzzle friendly: finding nonce such that H(nonce || x) < Y is hard



Hash pointers and data structures

- Hash pointer = pointer to data + hash of data
- Block chain: sequence of blocks whose integrity is maintained via hash pointers
- Optimization: Merkle trees
  - O(log n) check of data validity
  - Sorted Merkle: O(log n) check for invalid data block



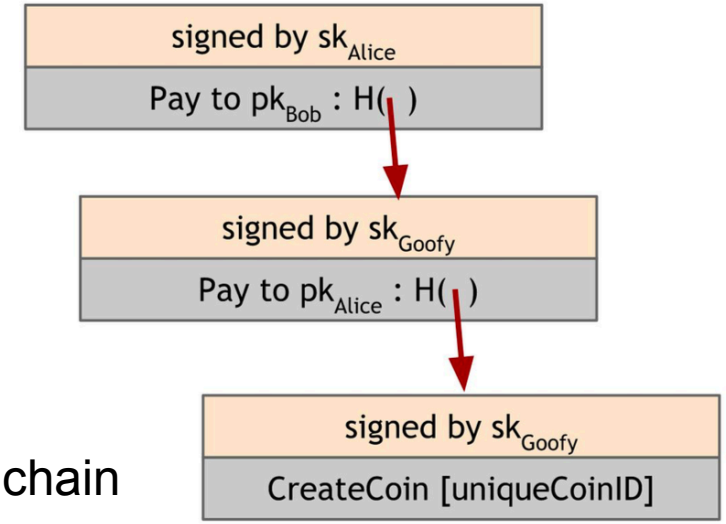
Digital signatures (PKI)

- Means of signing a transaction and proving ownership
- Implement via standard public key infrastructure (PKI), ala PGP
- Note: eliminates possibility of forging a message in Byzantine agreement problem

Preliminary Examples: GoofyCoin and ScroogeCoin

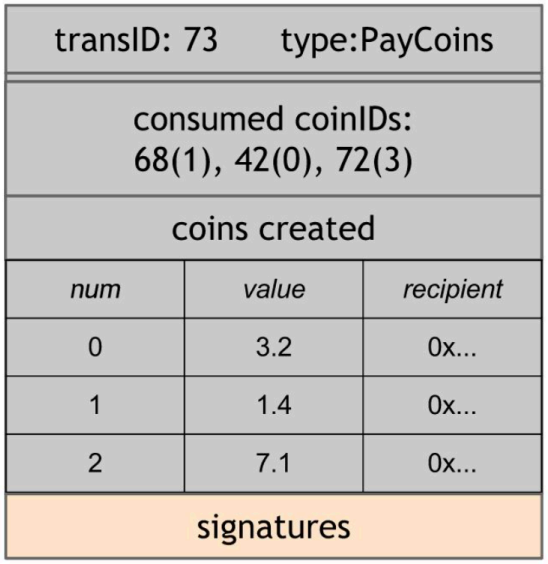
Goofy coin: simple block chain implementation

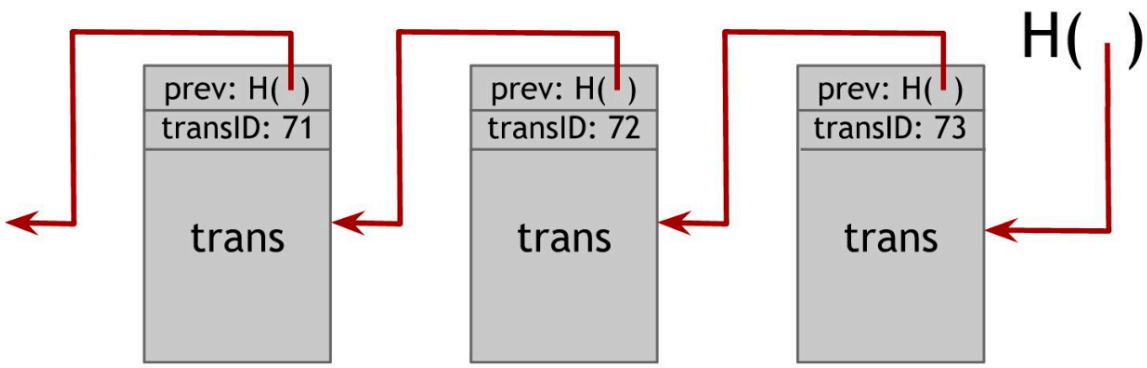
- Build chain of transactions, protected by hash pointers
- Start with set of coins and allow owners to spend
- Payee can verify payment by checking transfers
- Problem: coin owner can spent the same coin twice



ScroogeCoin:

- Mod #1: Implement append only ledger via transaction chain
  - Require banker to sign => avoid double-spend
- Mod #2: implement create and spend transactions
  - CreateCoins: create coin with unique ID
  - PayCoins: transfer coins between owners (with for ownership, validity, double-spend, etc)
- Problem: centralized solution (but we know what to do…)





Distributed Consensus for Distributed Ledger

Properties for distributed ledger

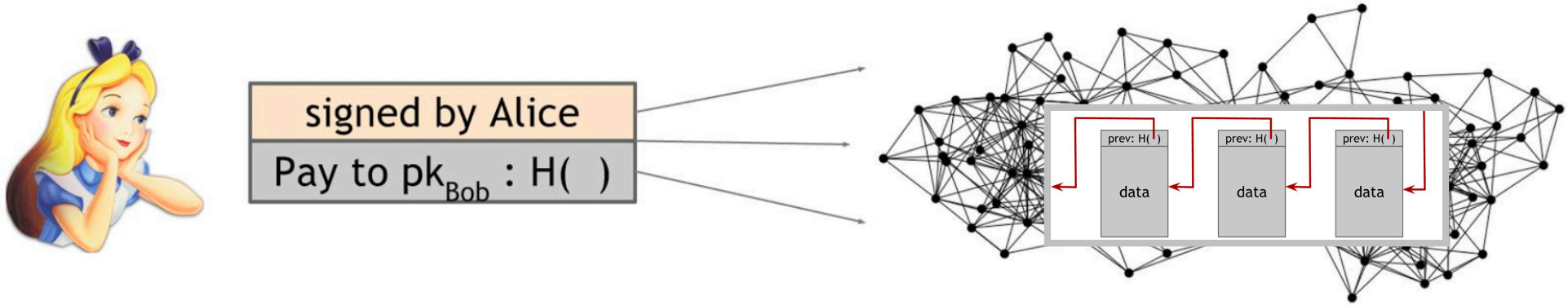
- Safety: stable(accepted transactions)
- Progress: valid transaction $\rightsquigarrow$ accepted

Distributed ledger using blockchain

- Implement standard distributed consensus (Paxos): agree on transactions (in blocks)
- No forged messages, but could see failed nodes, replay attacks, DDOS, etc
- Avoid coordinated attacks by implementing random choice of acceptors (= miners)

Bitcoin consensus algorithm (simplified)

- New transactions are broadcast to all nodes
- Each node collects new transactions into a block
- Each round, random node gets to broadcast its block
- Other nodes accept the block only if all its transactions are valid (signed, unspent, …)
- Nodes express acceptance of the block by including its hash in next block they create



Bitcoin Incentives and Proof of Work

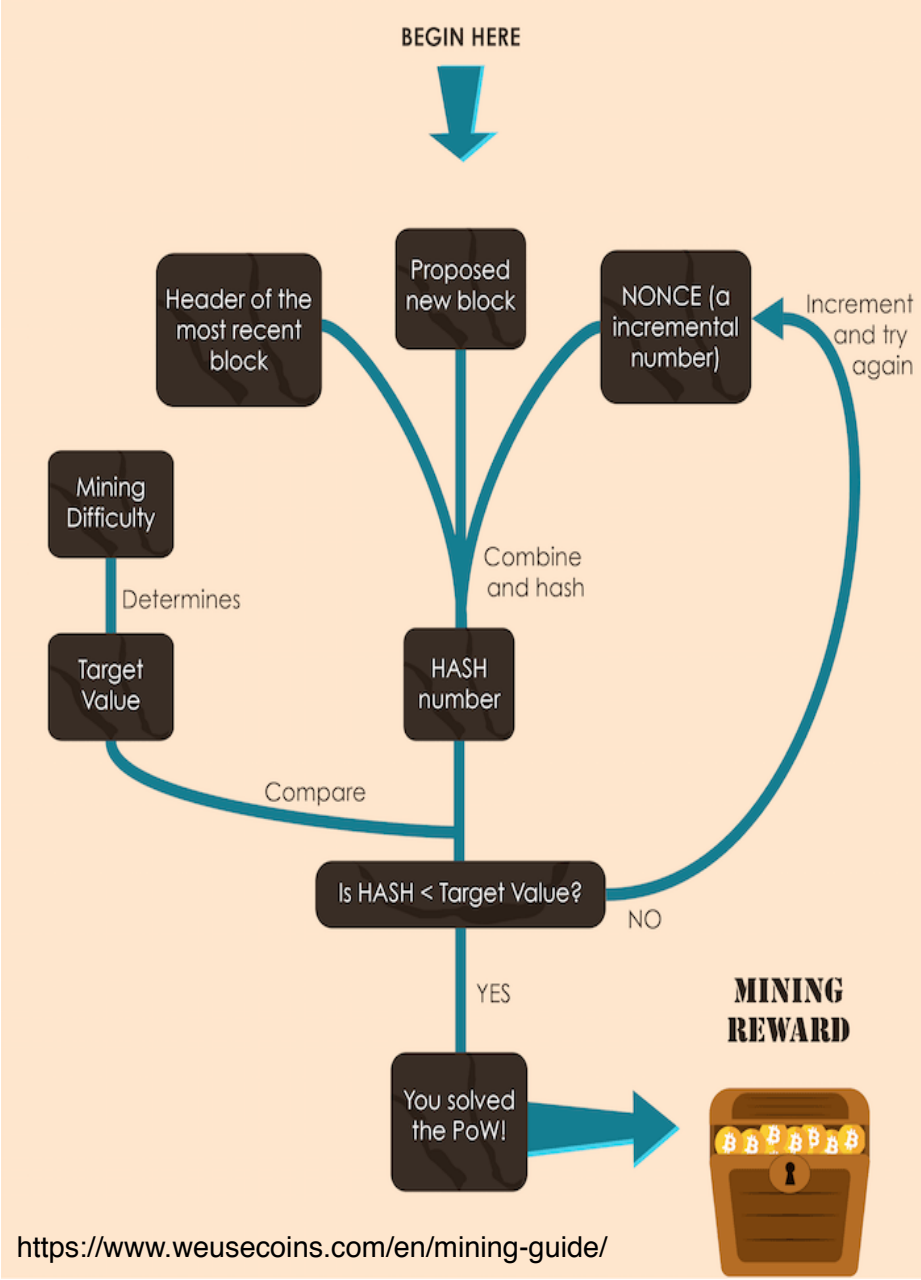
Bitcoin uses incentives to implement consensus

- Basic idea: trust nodes that spend lots of time doing useful work => traitors have to work (very) hard
- Reward #1: Block rewards = 12.5 BTC/ block created (today)
- Reward #2: Transactions fees = leave some change on the table

Mining and proof of work

- Miners must solve hash puzzle: create a nonce such that

  H(nonce || prevH || tx || ... || tx) < target
- Properties of hash function => this takes a long time on average (~10 min)
- Can propose a block of transactions whenever you solve the puzzle
- Use consensus algorithm to agree on blocks in chain (by building on them)



https://www.weusecoins.com/en/mining-guide/

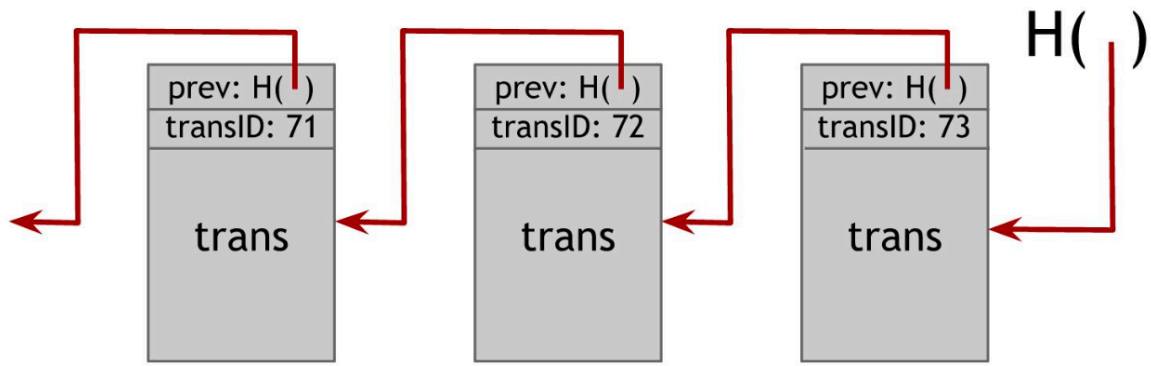
Bitcoin Attacks

Impersonation attack

- Not possible as long as crypto is strong enough

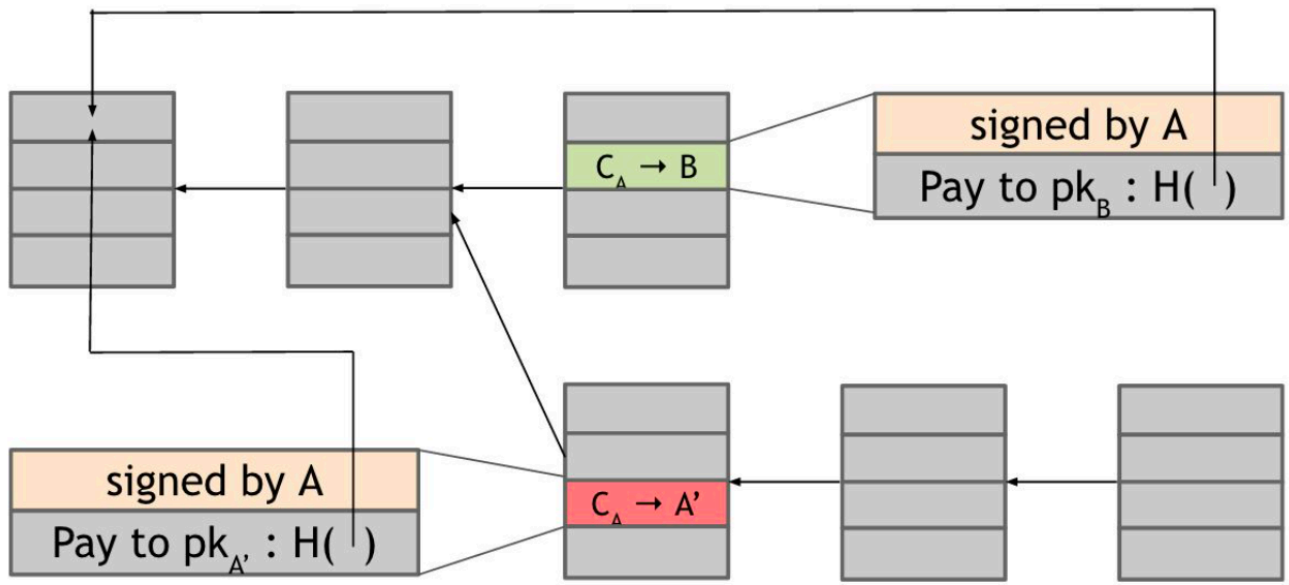
Change history attack

- Not possible as long as crypto is strong enough



Double spend attack

- What happens if you try to spend same coin twice?
- A: either one could be valid
- A: consensus will be achieved around the *longest* block => eventually one of the transactions will be selected by most miners
- Can show probability of the second block "winning" goes down exponentially in the number of blocks that have been built on the chain
- From a practical point of view, need to wait ~1 hour before providing goods…



Formal Analysis of Distributed Ledger (1 of 2)

No formal analysis of the safety of the Bitcoin protocol is yet available

- Safety properties are available, but not guarantee of progress
- Most proofs focus on showing the prefix of honest peers is stable

Problem specification (following Garay, Kiayias, Leonardos)

- Safety: All honest peers will have the same prefix for some depth k
- Progress: A conflict-free transaction will eventually be deeply confirmed in the blockchain of an honest peer

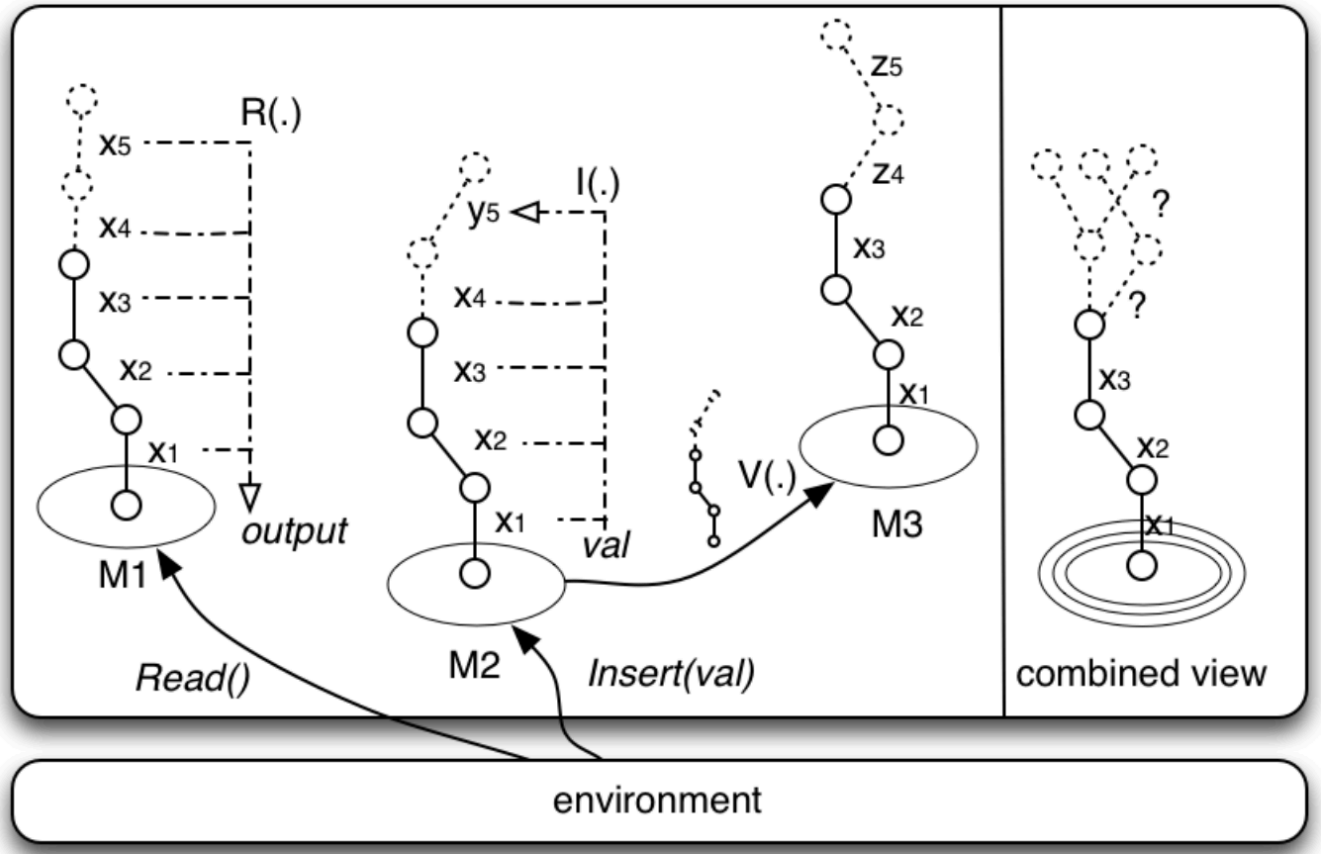
Formal definitions and analysis:

- Let C be a blockchain and let $C^{\lceil k}$ be the chain with the last k blocks removed
- Let n = number of players, t = number of traitors, $\mu = t/(n-t)$
- Common-Prefix Property: For any two honest players P1 and P2 adopting chains C1, C2 and round r1 = r2, it holds that $C1^{\lceil k} = C2^{\lceil k}$
- Chain Quality Property: For any host party P with chain C, it holds that for any ℓ consecutive blocks of of C, the ratio of adversarial blocks is at most μ
- Chain Growth Property: For any honest party P with chain C it holds that for any s rounds there are at least τ s blocks added to the chain

Formal Analysis of Distributed Ledger (2 of 2)

Bitcoin backbone protocol

- Read instruction [M1]: return content of chain
- Insert instruction [M2]: extend chain, solve proof-of-work, and broadcast extended chain to all
- Validate instruction [M3]: receive newly extended chain and adopt if better than local chain
- Note: miners agree on prefix to chain, but not on latest transactions



Properties of the protocol

- Likelihood that common prefix not present drops exponentially in length of chain
- Exponentially unlikely that adversary contributed to chain as the chain gets longer

Note: all properties are in terms of probabilities… (more on Wed)

Bitcoin Implementation

Surprising facts about Bitcoin

- Transaction data are unencrypted
- Transactions are coded using Forth-like language ("Script")
  - 1 byte opcode + arguments

Optimizations to make this work

- Transactions are kept small (~250 bytes/transaction)
- Blocks are stored as hashes of Merkle trees

Some current Bitcoin statistics

- Source: https://blockchain.info
- Number of miners: ~300K
- New blocks mined every 10 min
- Market price: $7,600/BTC
- Miner revenue: $15M/day
- Hash "difficulty": 13 x 10^{12}
- Size of blockchain: ~240GB

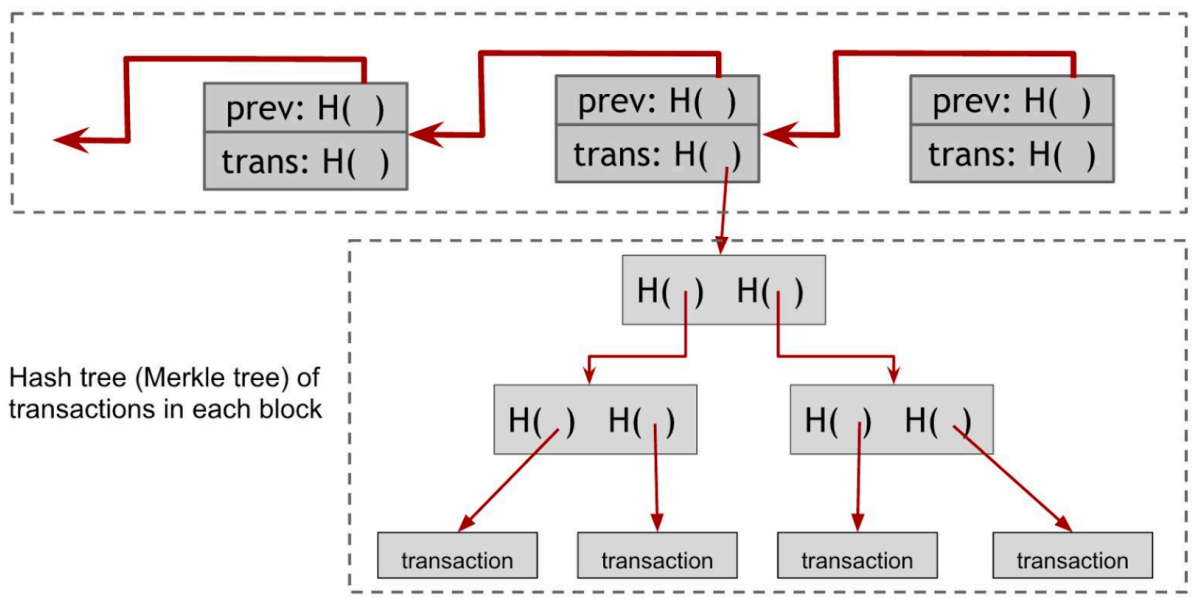
metadata

input(s)

output(s)

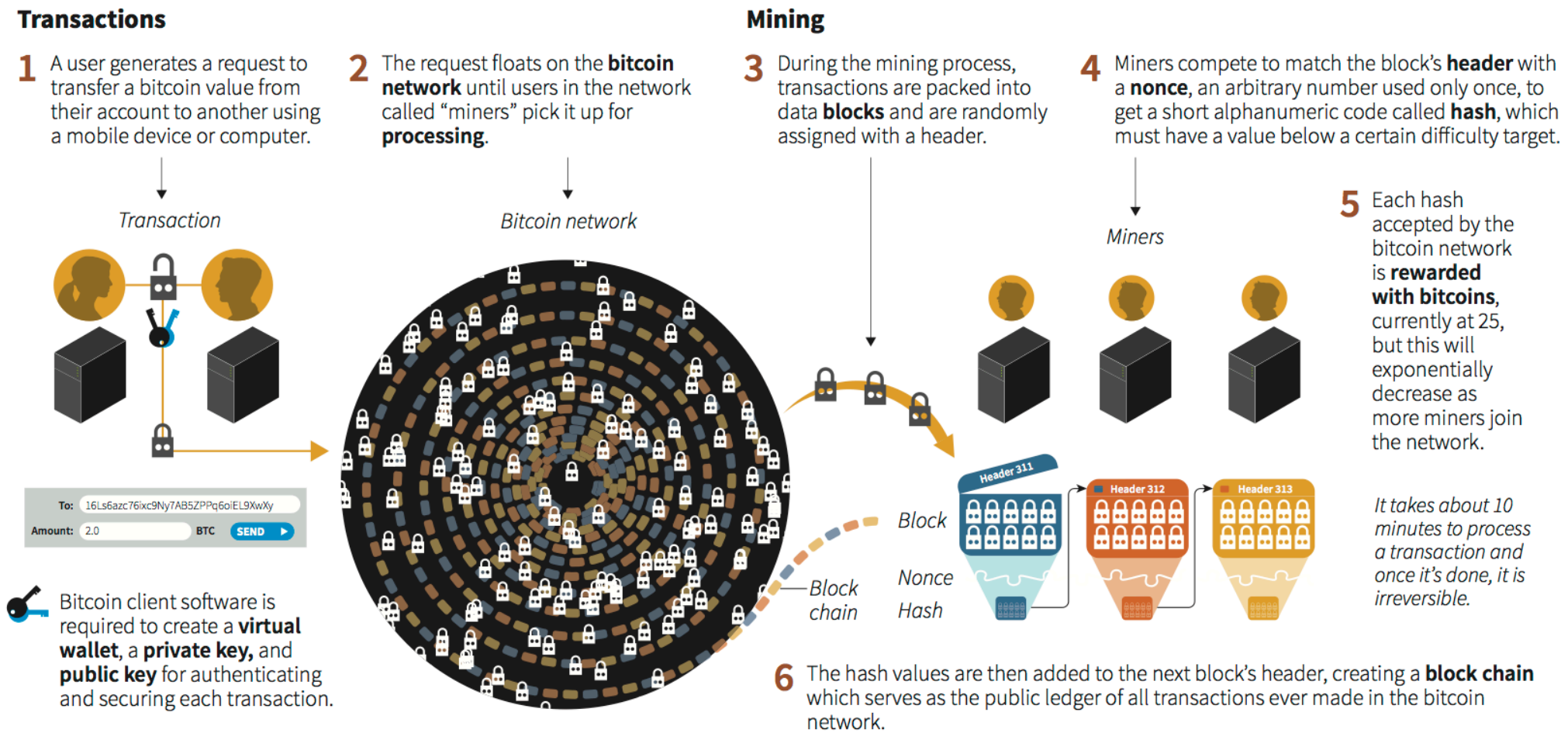

```
{
  "hash":"5a42590fbe0a90ee8e8747244d6c84f0db1a3a24e8f1b95b10c9e050990b8b6b",
  "ver":1,
  "vin_sz":2,
  "vout_sz":1,
  "lock_time":0,
  "size":404,
  "in":[
    {
      "prev_out":{
        "hash":"3be4ac9728a0823cf5e2deb2e86fc0bd2aa503a91d307b42ba76117d79280260",
        "n":0
      },

        "scriptSig":"30440..."
    },
    {
      "prev_out":{
        "hash":"7508e6ab259b4df0fd5147bab0c949d81473db4518f81afc5c3f52f91ff6b34e",
        "n":0
      },
      "scriptSig":"3f3a4ce81...."
    }
  ],
  "out":[
    {
      "value":"10.12287097",
      "scriptPubKey":"OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CH
    }
  ]
}
```


Hash chain of blocks



Hash tree (Merkle tree) of transactions in each block

Summary: Distributed Ledger and Bitcoin



Rest of the week:

- Wed: bitcoin probabilities
- Fri: final exam review

Richard M. Murray, Caltech CDS