# Distributed Systems

## CS425/ECE428

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*Instructor: Radhika Mittal*

*Acknowledgements for the materials: Nikita Borisov*

# Logistics

- Midterm scores were released on March 11th
  - The midterm scores will be curved.
  - We will open your assessment for viewing over a limited time window – stay posted for that.

- Tentative date and time for your final exam: May 12th 8-11am

# Agenda for today

- Consensus
  - Consensus in synchronous systems
    - *Chapter 15.4*
  - Impossibility of consensus in asynchronous systems
    - *We will not cover the proof in details*
  - Good enough consensus algorithm for asynchronous systems:
    - *Paxos made simple, Leslie Lamport, 2001*
  - Other forms of consensus algorithm
    - Raft (log-based consensus)
    - Block-chains / Bitcoins (distributed consensus)

# Bitcoins

- Implement a *distributed* replicated state machine that maintains an *account ledger (= bank).*
  - No user should be able to "double-spend".
  - Need to know of all transactions to validate this.
  - Who does this validation? Cannot trust a single central authority.
    - Any participant (replica) should be able to validate.
  - All replicas must agree on the single history on transaction ordering.
- Scale to thousands of replicas distributed across the world.
- Allow old replicas to fail, new replicas to join seamlessly.
- Withstand various types of attacks.

# Uses Blockchains for Consensus

- Why not use Paxos / Raft?
  - Need to scale to thousands of replicas across the world.
  - May not even know of all replicas a priori.
  - Participants may leave / join dynamically.
  - Paxos/Raft are ill-suited for such a setup.
    - Leader election in Raft or proposals in Paxos require communication with at least a majority of servers.
    - Require knowing the number of replicas.
    - ….

- *So how does blockchain work?*
  - Focus of today's class. Only a high-level discussion.

# Basic Idea

Transactions grouped into a *block* that gets added to the *chain* (history of transactions) by the "leader of that block".

# Lottery Leader Election

- Every node chooses a random number

- Leader = “closest to 0”

# Lottery Leader Election

- Every node chooses a random number
  - The method for choosing the number in blockchains enables log consensus (with a high probability).
  - Requires the leader to expend CPU (as *proof-of-work*).

- Leader = "closest to 0"
  - Defined such that a replica can determine this independently without coordination

# Choosing the random number

- Cryptographic hash function:
  - H(x) -> { 0, 1, ..., $2^{256}$-1}
- Hard to *invert:*
  - Given y, find x such that H(x) = y
  - E.g., SHA256, SHA3, ...
- Every node picks random number x and computes H(x)
- Node with H(x) "closest to 0" wins
  - Finding such an x requires expending CPU (*proof-of-work*).

- *But once we have found an 'x', we can always be the leader for all blocks, or even share it with colluding parties. How to prevent that?*

# Using a seed

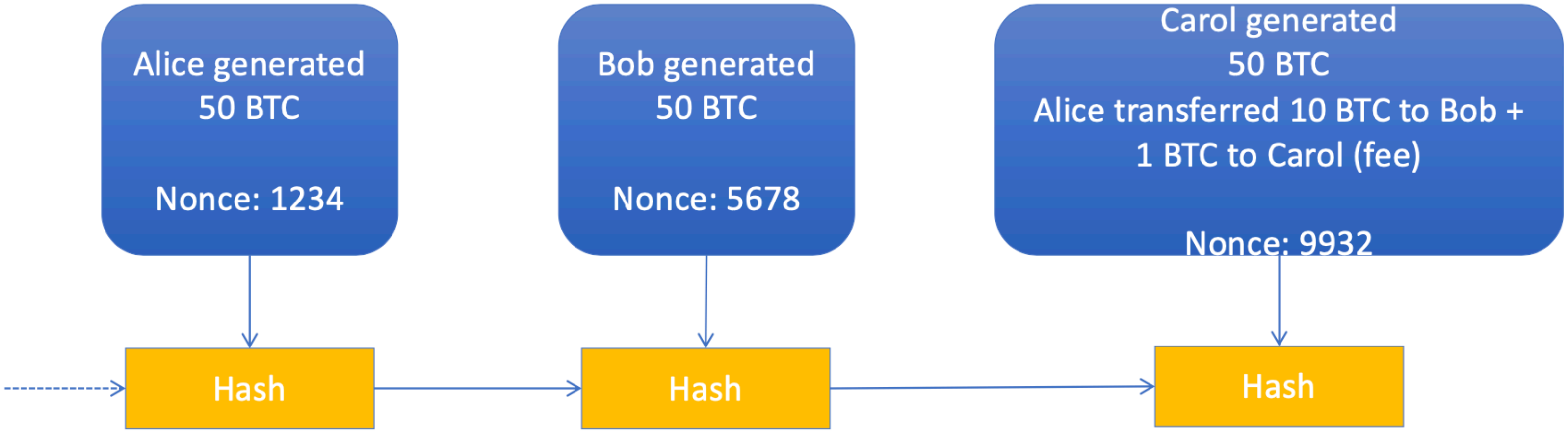
- Every node picks x, computes H(seed || x)
- Closest to 0 wins
- What to use as a seed?
- Hash of:
  - Previous log
  - Node identifier
  - New messages to add to log

- *How to find "closest to 0"?*

# Iterated Hashing / Proof of work

- Repeat:
  - Pick random $x$, compute $y = H(seed \,||\, x)$
  - If $y<T$, you win!
- Set threshold $T$ so that on average, one winner every few minutes
- Given a *solution*, $x$ such that $H(seed \,||\, x) < T$, anyone can *verify* the solution in constant time (microseconds).

# Chaining the blocks




| Account | Balance |
|---|---|
| Alice | 39 BTC |
| Bob | 60 BTC |
| Carol | 51 BTC |

# Protocol Overview

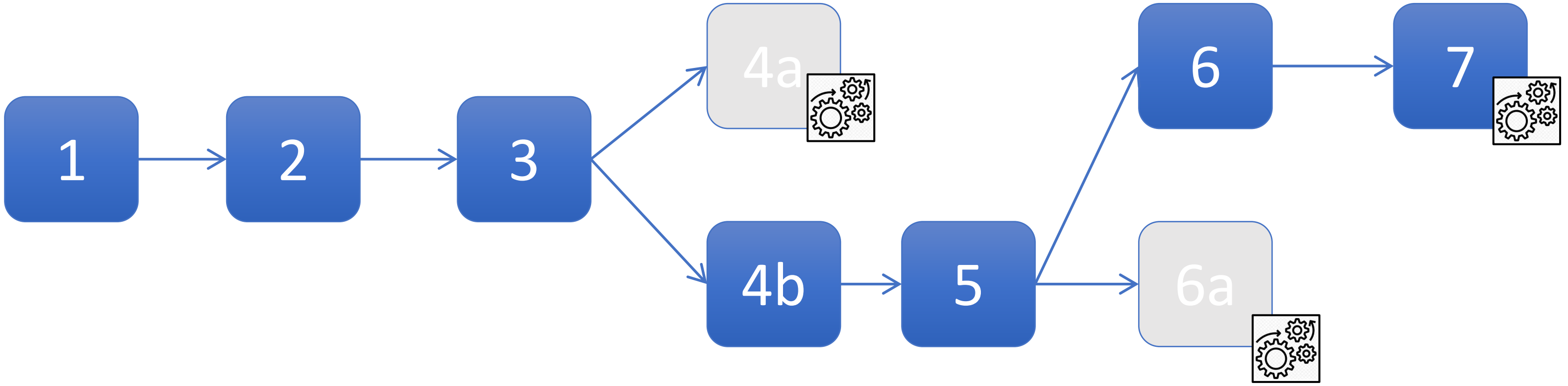
- New transactions broadcast to all nodes.
- Each node collects new transactions into a block.
- Each node works on finding a proof-of-work for its block to become its leader and get it appended to a chain.
  - i.e. finds x, such that $H(seed \,||\, x) < T$.
- When a node finds a proof-of-work, it broadcasts it to all nodes.
- Nodes accept a block only if all transactions in it are valid.
- Nodes express their acceptance by working on creating the next block in the chain, using the hash of accepted block as previous hash.

# What could go wrong?

- Two nodes may end up mining different versions of the next block.

# Longest Chain Rule

- Two nodes may end up mining different versions of the next block.
- A node may receive two versions of the next block.
- Will store both, but work on the first one they receive.
- Over time, more blocks will be received.
- The node will switch to working on the *longest chain*.



# When is a transaction committed?

- Wait for upto k more blocks to be added in the chain.
- Then commit the transaction.
- k is set to 6 for Bitcoins.

# Security Property

- Majority decision is represented by the longest chain.
  - It has greatest "proof-of-work" invested in it.

- If majority of CPU power is controlled by honest nodes, the honest chain will grow fastest and outpace competing chains.

- To modify past blocks, an attacker will need to redo the proof-of-work for that block, and all blocks after it, and then surpass the work of honest nodes.

- Probability of attack reduces as more blocks get added.

# Incentives for Logging

- Security better if more people participated in logging.
- Incentivize users to log *others*' transactions
  - Transaction fees: e.g. pay me x% to log your data (or some fixed fee per transaction)
  - Mining reward: each block *creates* bitcoins

# Logging Speed

- How to set T?
  - Too small: slows down transactions
  - Too big: wasted effort due to chain splits

- Periodically adjust difficulty T such that one block gets added every 10 minutes.
  - Depends on hardware speed (which typically improves over time) and number of participants (which vary over time).

- Determined algorithmically based on the rate at which blocks are mined
  - Target is 1 block every 10minutes.
  - Difficulty recomputed after every 2016 blocks.

# Bitcoin Broadcast

- Need to broadcast:
  - Transactions to all nodes, so they can be included in a block.
  - New blocks to all nodes, so that they can switch to longest chain.

- What if we use R-multicast?
  - Have to send O(N) messages
  - Have to *know* which nodes to send to
  - Not a suitable choice.

# Gossip / Viral propagation

- Each node connects to a small set of *neighbors* (10–100).
- Nodes propagate transactions and blocks to neighbors.
- Push method: when you hear a new tx/block, resend them to all (some) of your neighbors (flooding).
- Pull method: periodically poll neighbors for list of blocks/tx's, then request any you are missing.
- Unreliable: some nodes may not receive all transactions or all blocks. But that's ok.

# Maintaining Neighbors

- A *seed* service
  - Gives out a list of random or well-connected nodes
  - E.g., seed.bitnodes.io

- Neighbor discovery
  - Ask neighbors about *their* neighbors
  - Randomly connect to some of them

# Bitcoin Summary

- Unreliable broadcast using gossip
- Probabilistic "leader" election for mining blocks (tx ordering)
- Longest chain rule to ensure long-term (probabilistic) consistency and security

- Compared with Paxos/Raft:
  - Scales to thousands of participants, dynamic groups
  - Tens of minutes to successfully log a transaction (vs. milliseconds)