Distributed Systems

CS425/ECE428

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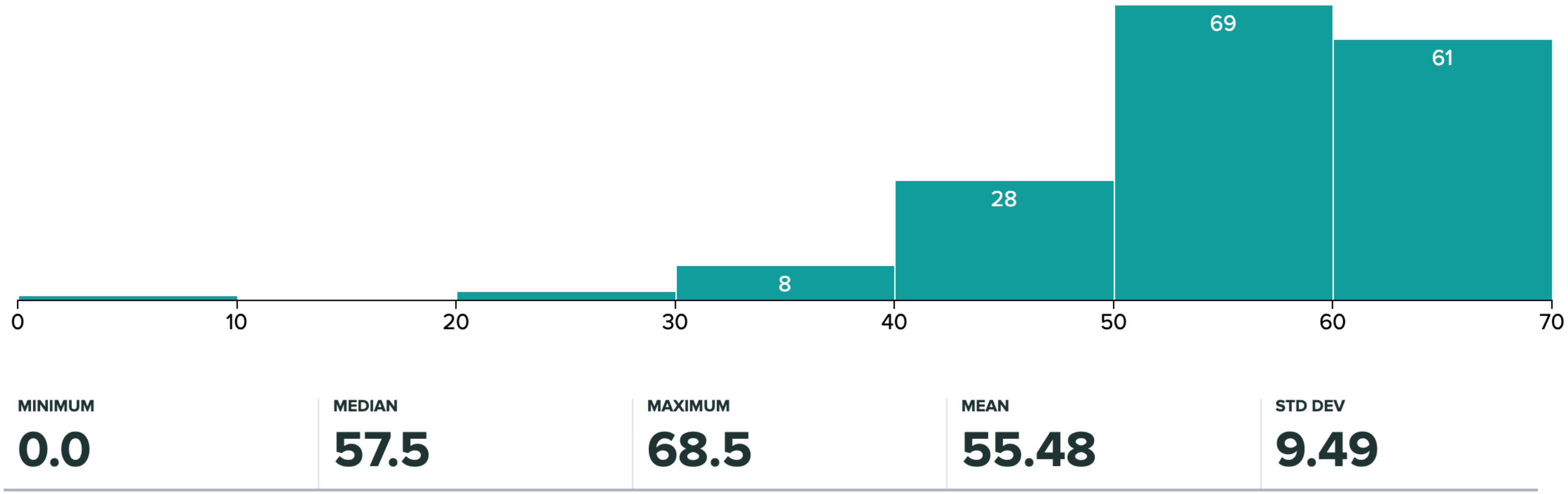
Acknowledgements for the materials: Nikita Borisov

Logistics

- Midterm 1 grades were released on Monday.



MINIMUM	MEDIAN	MAXIMUM	MEAN	STD DEV
0.0	57.5	68.5	55.48	9.49

Logistics

- Midterm 2 on April 5th, Monday, 7-8:50pm CT.
- Same format as Midterm 1.
    - Checkout my CampusWire post on CBTF photo requirement.

- Syllabus: Everything covered beyond the syllabus of Midterm1 upto and including Raft.
    - Mutual Exclusion
    - Leader Election
    - Consensus
        - Synchronous consensus
        - Asynchronous consensus (Paxos, Raft)
    - *(Blockchain and beyond not included in Midterm 2 syllabus.)*
    - *(Midterm 1syllabus not included in Midterm 2 syllabus.)*

Recap

- Log consensus / Replicated State Machines
  - Need to ensure the log entries / commands are processed in the same order at different servers.
  - Same requirement as total reliable multicast.

- Paxos is the most popular consensus algorithm for asynchronous system. Multi-paxos for log consensus.
  - Difficult to understand and implement.

- Raft designed for simplicity.

Recap: Raft

- Elect a leader. Only leader can add and commit log entries.
  - Tries to eventually make other server's logs identical to its own.
- Handling failures: each new leader election increments the *term*. Terms increase monotonically over time.
- Raft design provides various forms of guarantees:
  - Only one leader elected per term
    - A server can only grant one vote per term. Need majority to win.
  - If log entries on different servers have same index and term, they store the same command, and the logs are identical in all preceding entries.
    - Consistency check when appending a new entry.
  - If a leader has decided that a log entry is committed, that entry will be present in the logs of all future leaders.
    - Restrictions on commitment and leader election.
- Together ensure: *Once a log entry has been applied to a state machine, no other state machine must apply a different value for that log entry.*

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

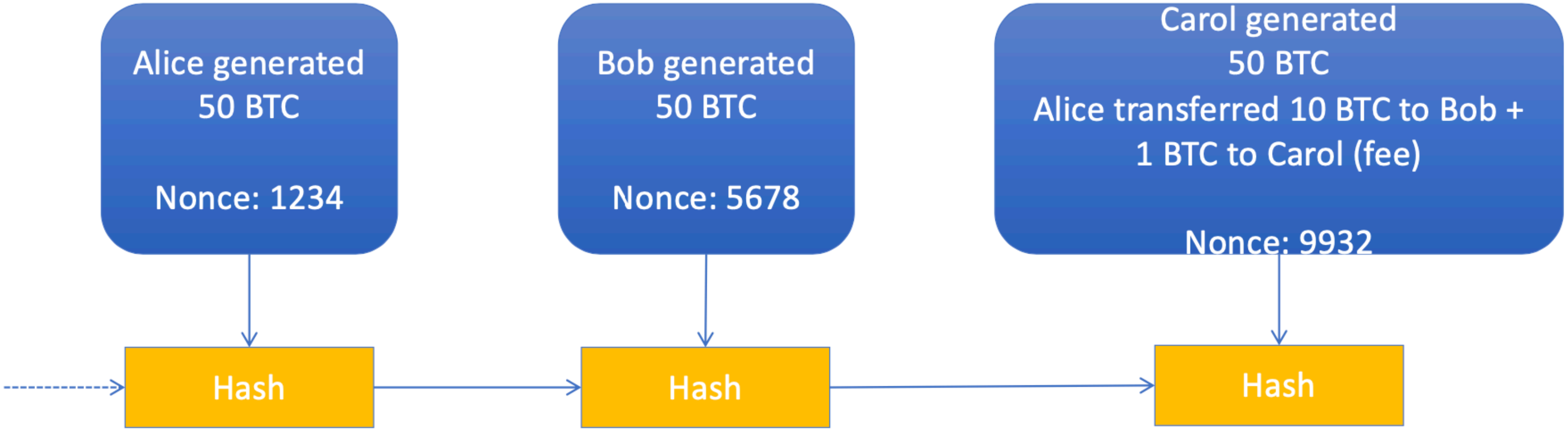
- Every node picks x, computes H(seed || x)
- Closest to 0 wins
- What to use as a seed?
- Hash of:
  - Previous log
  - Node identifier
  - New messages to add to log

- *How to find “closest to 0”?*

Iterated Hashing / Proof of work

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

Chaining the blocks



Alice generated 50 BTC

Nonce: 1234

Bob generated 50 BTC

Nonce: 5678

Carol generated 50 BTC
Alice transferred 10 BTC to Bob + 1 BTC to Carol (fee)

Nonce: 9932

Account	Balance
Alice	39 BTC
Bob	60 BTC
Carol	51 BTC

Protocol Overview

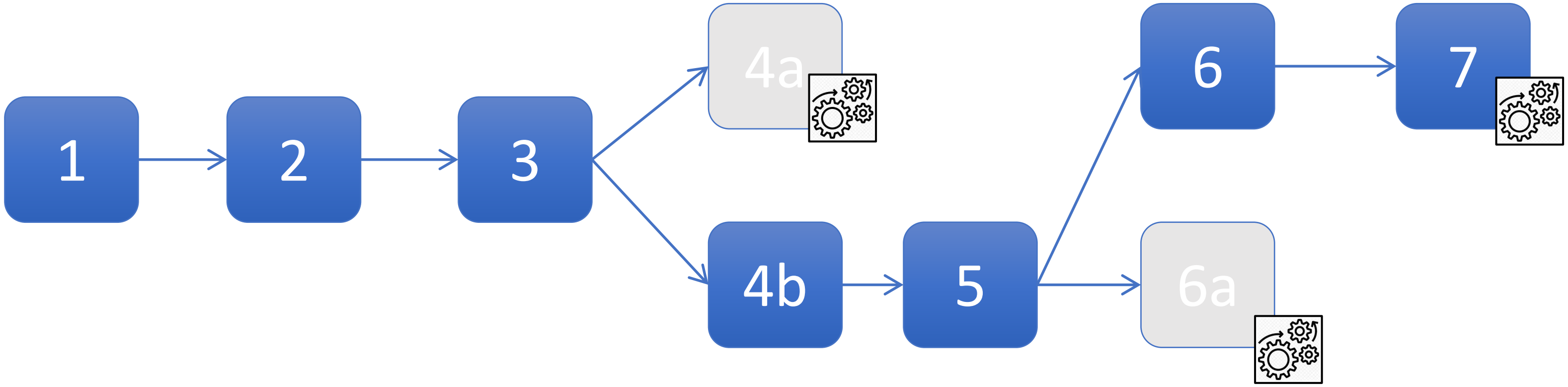
- New transactions broadcast to all nodes.
- Each node collects new transactions into a block.
- Each node works on finding a proof-of-work for its block to become its leader and get it appended to a chain.
    - i.e. finds x, such that $H(seed \,||\, x) < T$.
- When a node finds a proof-of-work, it 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*.



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: pay me x% to log your data
  - Mining reward: each block *creates* bitcoins

Logging Speed

- How to set T?
    - Too large wasted effort due to broadcast delays & chain splits
    - Too small: slows down transactions

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

- Determined algorithmically based on measured average number of blocks mined per hour.

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)