Bitcoin and Nakamoto Consensus

Distributed Systems, Spring 2020

Nikita Borisov

Topics for Today

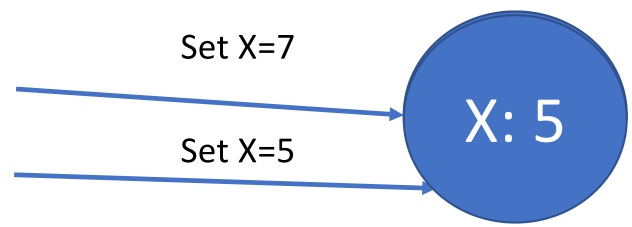
- Replicated State Machines and Log Consensus
- Bitcoin
  - Consensus approach
  - Transaction broadcast
- MP2 overview

Announcements

- Midterm grades are out: med 52, mean 52.7, STD 6.73 (out of 70)
  - Regrades are due by 11pm on Mar 25th
  - Solution will be released today/tomorrow
- MP2 out today
  - Due on April 13
- HW3 **extended** till **Monday 16**
- HW4 out Friday, due **April 2**
  - **No extensions**
- Midterm 2 on **April 6**

State Machine

- A process with some ***state*** that responds to ***events***



Banks

- State: account balances
  - Alice: $100
  - Bob: $200
  - Charlie: $50
- Events: transactions
  - Alice pays Bob $20
  - Charlie pays Alice $50
  - Charlie pays Bob $50

Databases (e.g., enrollment)

- State: database tables
  - Classes:
    - Alice: CS425, CS438
    - Bob: CS425, CS411
    - Charlie: ECE428, ECE445
  - Rooms:
    - CS425: DCL1320
    - ECE445: ECEB3013
- Events: transactions
  - Alice drops CS425
  - Bob switches to 3 credits
  - Charlie signs up for CS438
  - ECE445 moves to ECEB1013

Filesystems

- State: all files on the system
  - Midterm.tex
  - HW2-solutions.tex
  - Assignments.html

- Events: updates
  - Save midterm solutions to midterm-solutions.tex
  - Append MP2 to Assignments.html
  - Delete exam-draft.tex

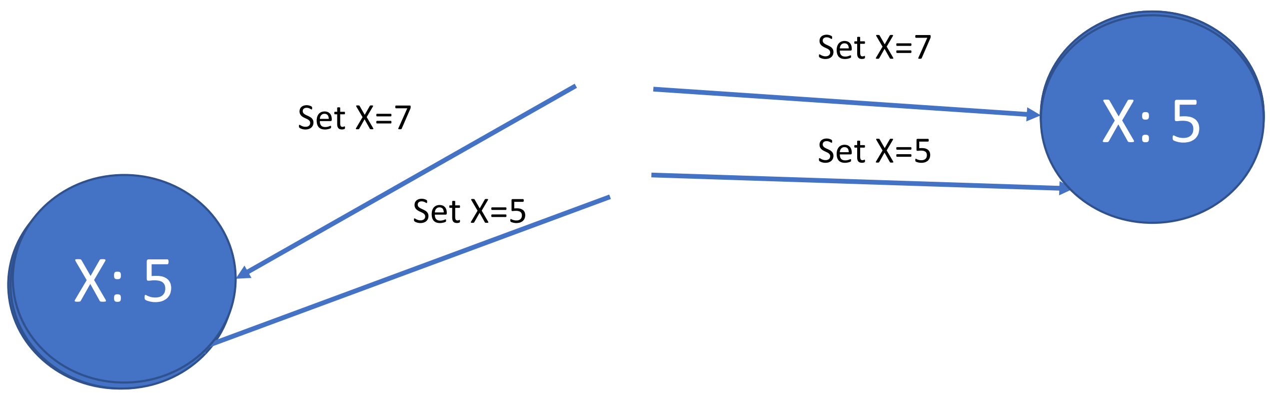
State machines

- State: complete state of a program

- Events: messages received

- Assumption: all state machines deterministic

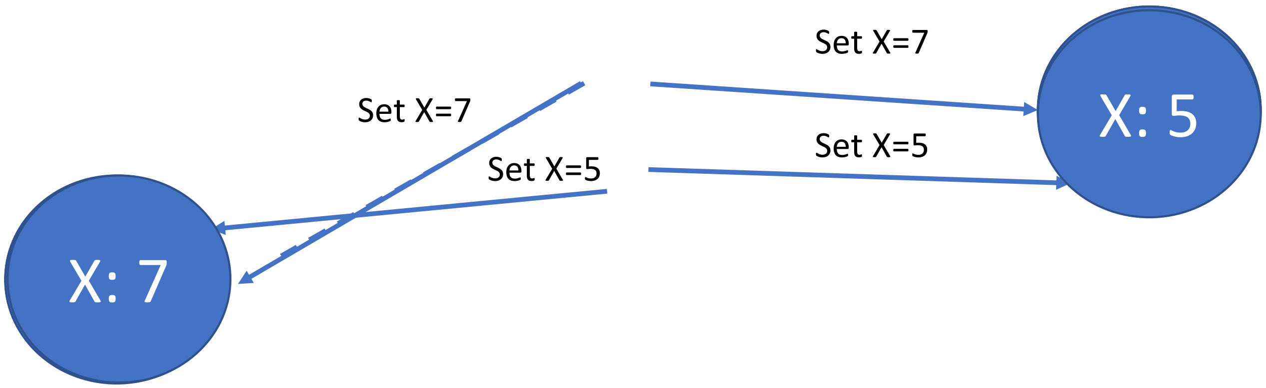
Replicated state machines



Replicated State Machines

- A state machine can fail, taking the state with it
- Replicate for
  - Availability — can continue operation even if one SM fails
  - Durability — data is not lost
- Must ensure:
  - Consistency!

Consistency



Consistency Requirement

All state machines must process

- The same set of events
  - **R-multicast**
- In the same order
  - **Total ordering**

Other requirements

- Same initial state
- Deterministic execution

Log Consensus

- Reliable, totally-ordered multicast == Consensus
- TO multicast can implement consensus (how?)
- Consensus can implement TO multicast (how?)
- Event ordering / log consensus: main application of consensus protocols!

Bitcoin

- Implement a distributed, replicated state machine that maintains an *account ledger (= bank)*
- Scale to thousands of replicas distributed across the world
- Allow old replicas to fail, new replicas to join seamlessly
- Withstand various types of attacks

Approaches that don't work

- Totally ordered multicast (e.g., ISIS)
  - Quadratic communication overhead
  - Do not know who all replicas are a priori
- Leader election (e.g., Bully)
  - Quadratic communication overhead
  - Do not know who all replicas are a priori
  - *Nodes with highest IDs are leaders =>*
    - Bottleneck
    - Security

Lottery Leader Election

- Every node chooses a random number
- Leader = closest to 0

Hash Functions

- 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

Using a seed

- Every node picks x, computes H(seed || x)
  - Closest to 0 wins

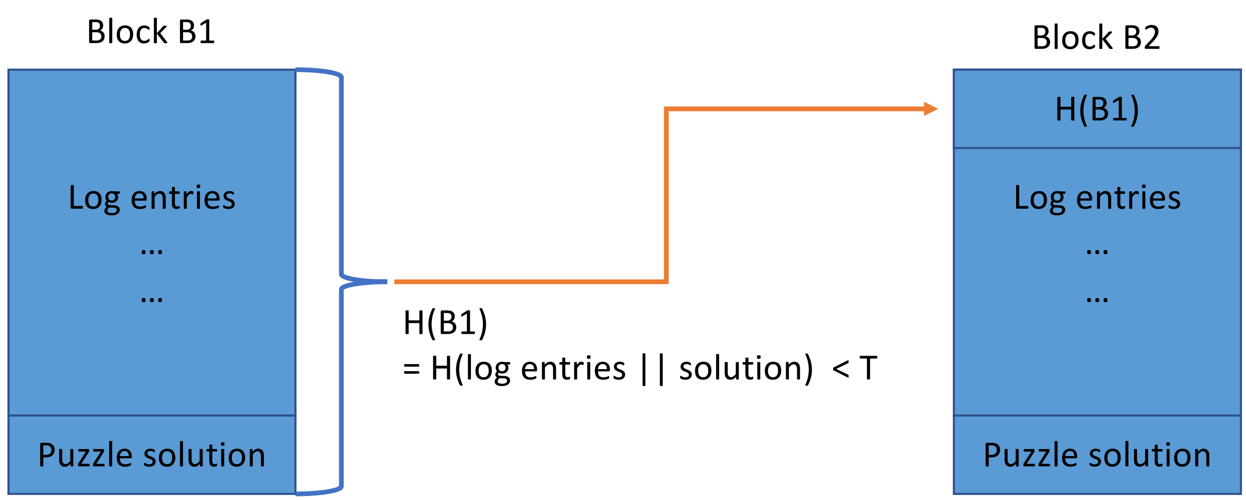
What to use as a seed?

- Hash of:
  - Previous log
  - Node identifier
  - New messages to add to log
- Two remaining problems:
  - How to find closest to 0?
  - How to prevent nodes from trying multiple random numbers?

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
- E.g.:
  - 1000 nodes
  - 10^12 hash/second
  - Target interval: 10 minutes
  - T = ?
- Given a *solution*, x such that H(seed || x) < T, anyone can *verify* the solution in constant time (microseconds)

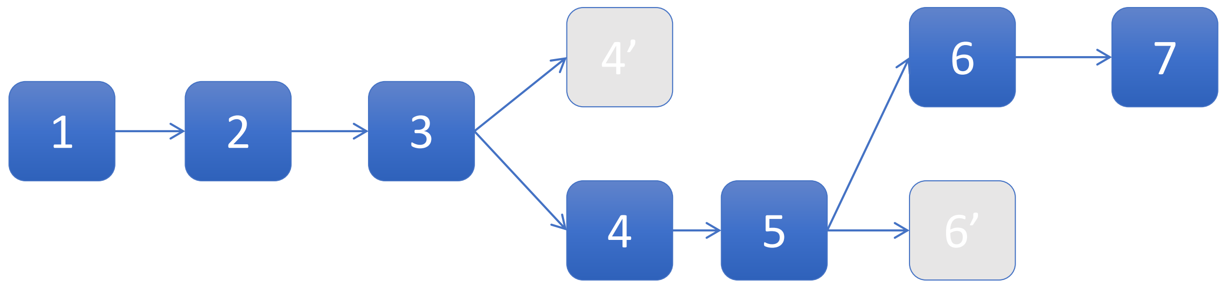
Block



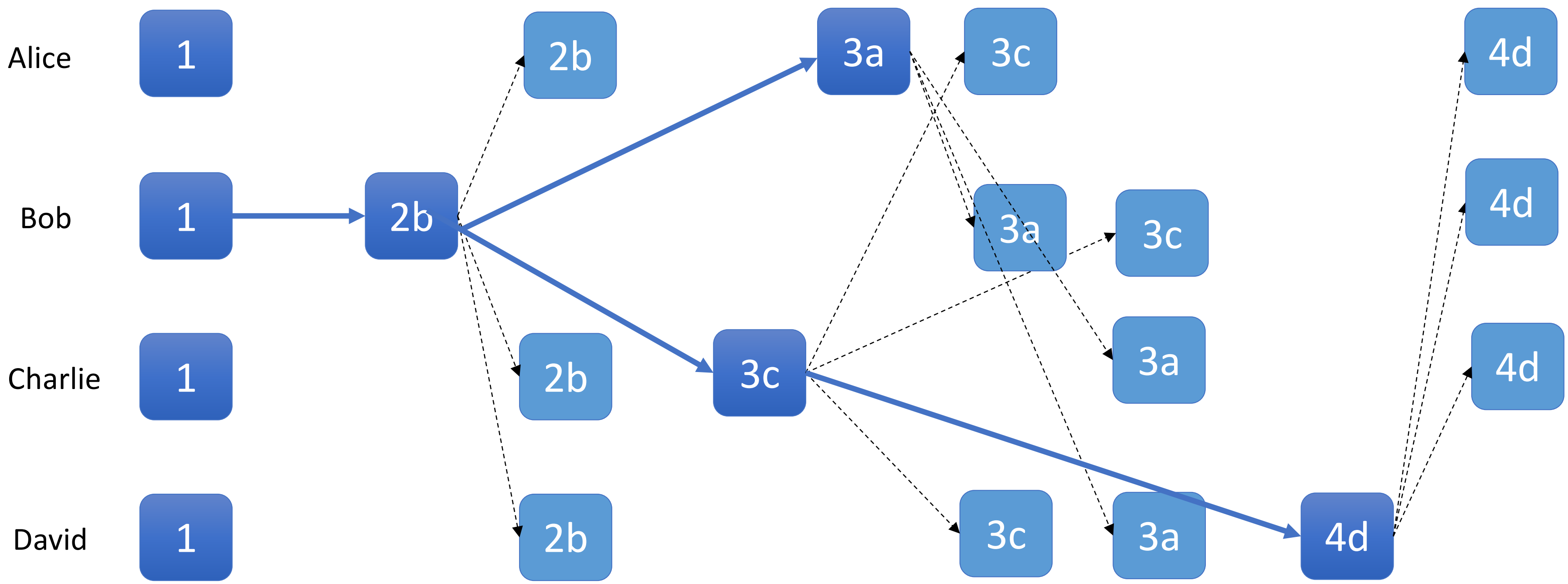
Block B1
Log entries
…
…
Puzzle solution
H(B1)
= H(log entries || solution) < T
Block B2
H(B1)
Log entries
…
…
Puzzle solution

Chaining

- Each block's puzzle depends on the previous one
  - L_n -> L_{n-1} -> … -> L_1 -> L_0
  - To add m blocks, must solve m puzzles
- Longest chain wins



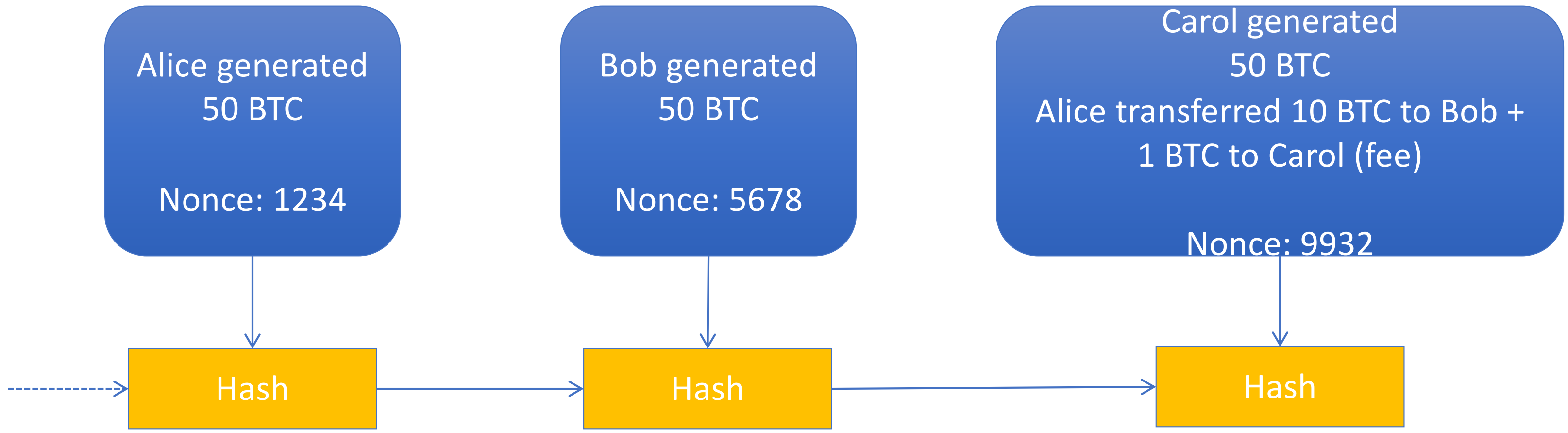
Chain evolution



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
    - Replace "Alice minted x" entries with "Alice logged line L_n"
- Payment protocol:
  - Alice->Bob: here's coin x
  - *Broadcast* to everyone: Alice transfers x to Bob
  - Bob: wait until transfer appears in a new log line
    - Optionally wait until a few more lines follow it

Putting it all together



Account	Balance
Alice	39 BTC
Bob	60 BTC
Carol	51 BTC

Logging Speed

- How to set T?
  - Too short: wasted effort due to broadcast delays & chain splits
  - Too long: slows down transactions
- Periodically adjust difficulty T such that one block gets added every 10 minutes
  - Determined algorithmically based on timestamps of previous log entries
- Current difficulty
  - $7 * 10^{22} =\sim 2^{76}$ hashes to win
- Large number of participants: hard to revise history!

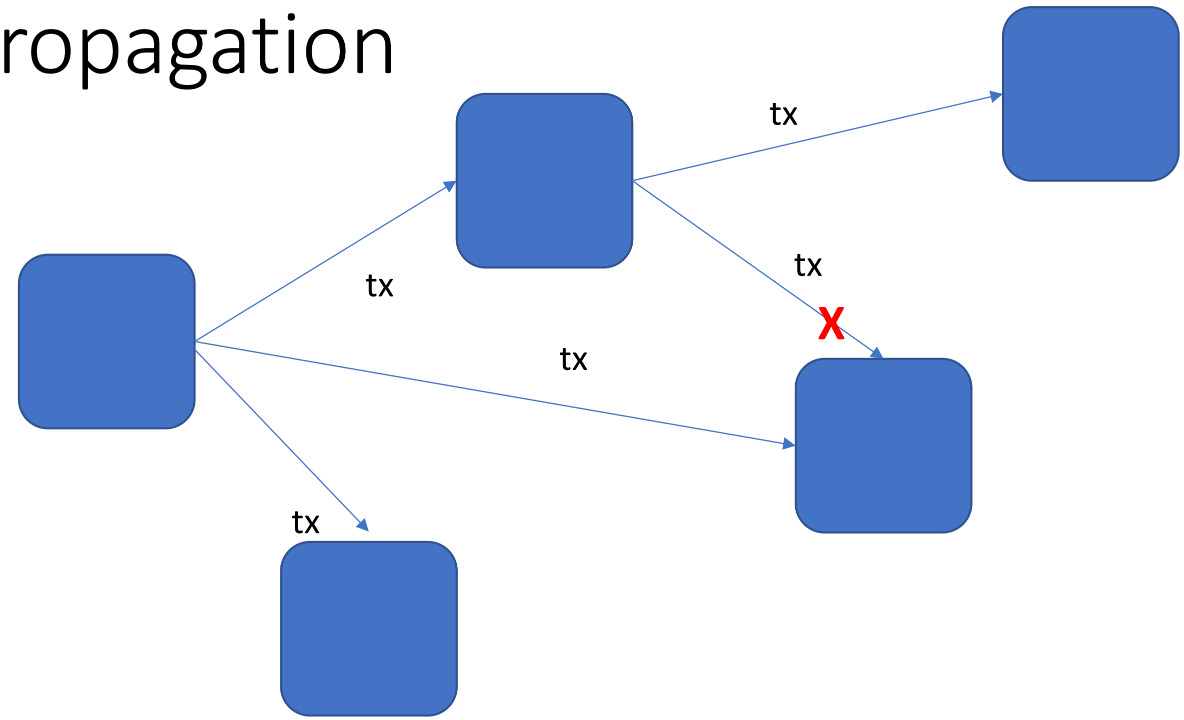
Bitcoin broadcast

- 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
- Why not R-multicast?
  - Have to send O(N) messages
  - Have to *know* which nodes to send to

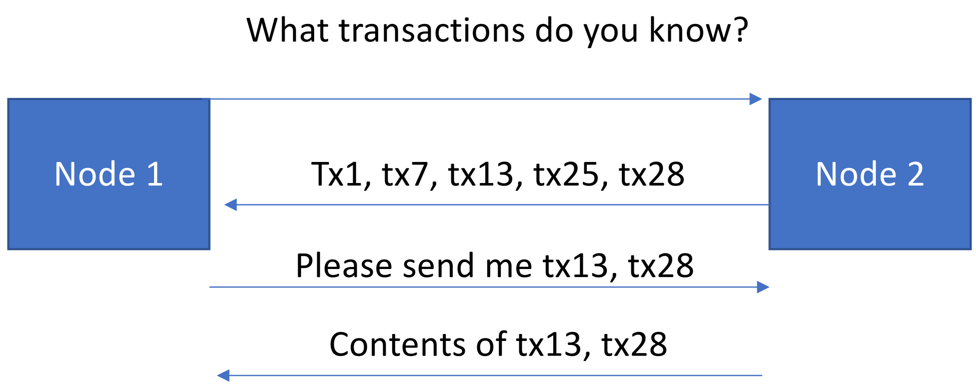
Gossip / Viral propagation

- 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

Push propagation

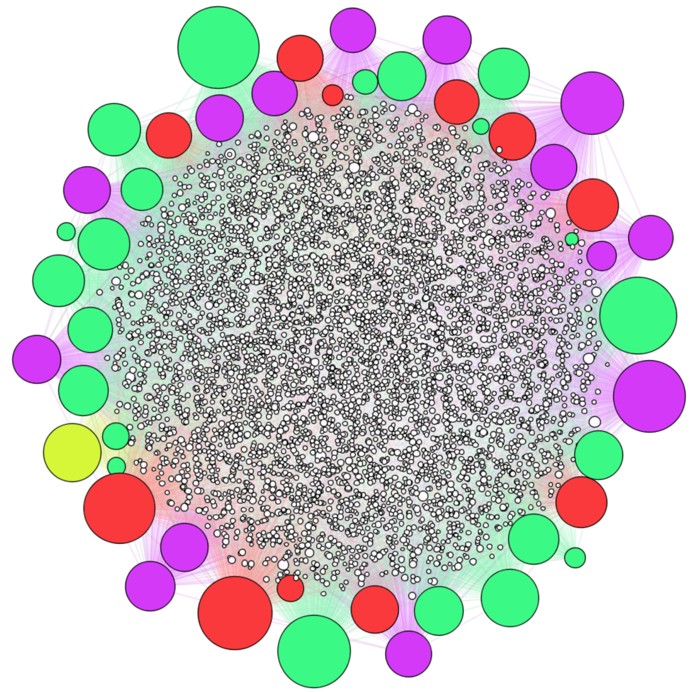


Pull propagation



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

Foundations:

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

Compared with Paxos/Raft:

- Scales to thousands of participants, dynamic groups
- Tens of minutes to successfully log a transaction (vs. milliseconds)