Blockchains & Distributed Ledgers

Lecture 06

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Permissionless Protocols

- Bitcoin and similar PoW-based blockchain protocols operate in the **permissionless** setting:
  - Anyone can participate in the protocol and receive BTC as rewards by performing the PoW-based mining operation
  - Parties can come and go as they wish – no permission is required.
- **Minting new coins** (via PoW) makes it feasible for anyone (possessing sufficient hashing power) to participate
- The ledger itself is public, readable and writeable by anyone
  - read (retrieve ledger information): connect to the network and download the ledger
  - write (insert new information to the ledger): obtain some bitcoins and create a transaction
- **Sybil resilience**:
  - Relies on computational power: it doesn't matter how many relays/nodes the adversary controls – what matters is its computational power.

Dynamic Availability

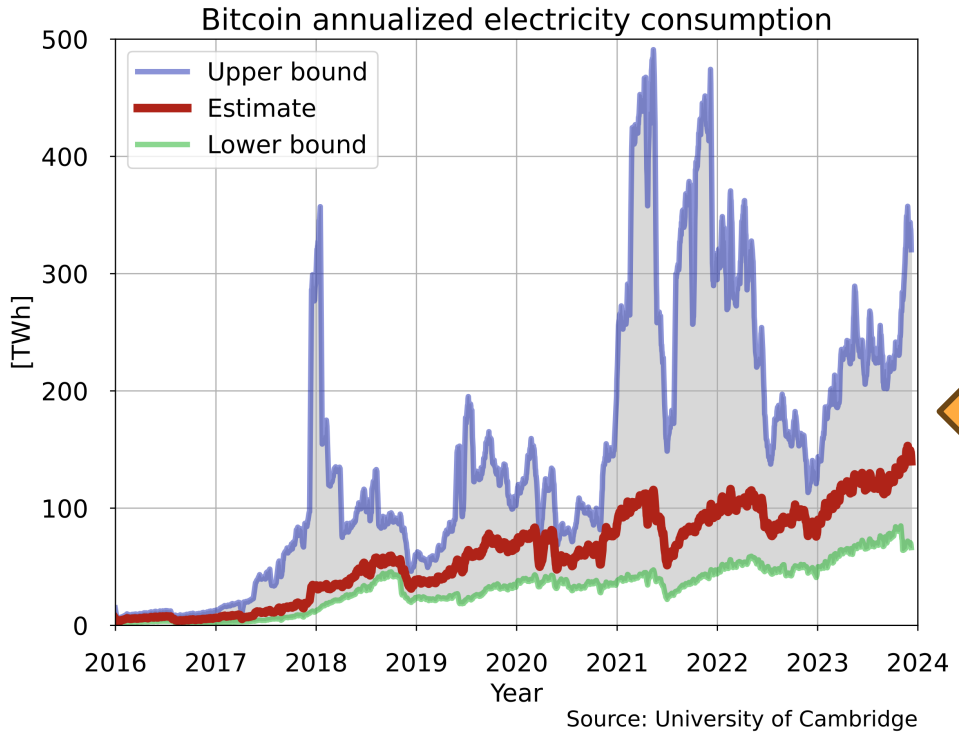
- Parties join and leave at will
- Need to bootstrap a chain when (re)joining):
  - Bitcoin's *"longest chain rule"* (most difficult chain)
- Number of online/offline parties changes over time
  - Analysis must account for that
- No *a priori* knowledge of participation levels
- Unannounced disappearance

Classic BFT protocols *do not* operate under general dynamic availability

Bitcoin’s Energy Problem

- Bitcoin resolves dynamic availability via PoW
  - Parties have limited access to a resource (computational power)
  - They repeatedly try to solve cryptographic puzzles (hashes)
  - A puzzle solution allows to create a block and append it to the chain
- Bitcoin is energy **inefficient**
  - The resource employed is physical (is this protocol the best use of it?)
  - The hash-based lottery consumes energy to ensure the protocol’s security
    - An energy arms race between the good guys and the (potential) bad guys
  - Bitcoin presumes that it is under attack *at all times*

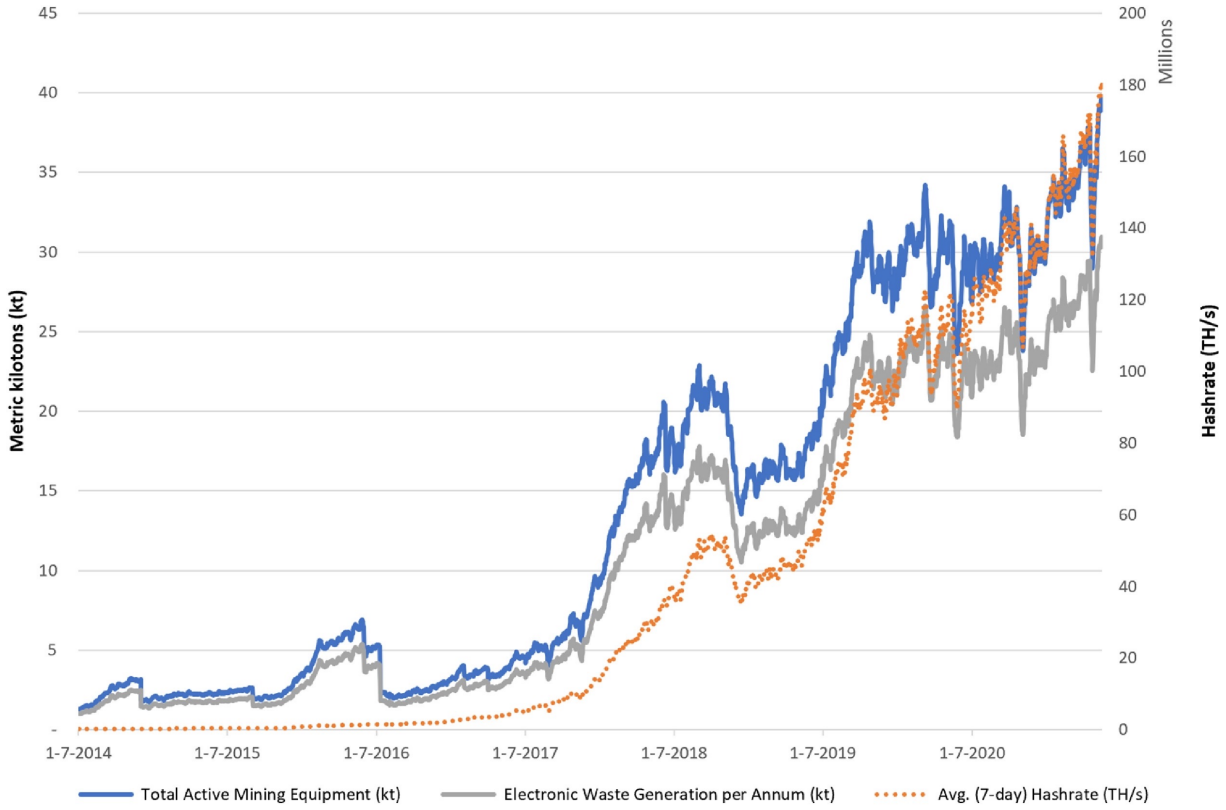
Bitcoin’s Energy Problem - electricity consumption



Many european countries
Are in this range

https://en.wikipedia.org/wiki/Environmental_impact_of_bitcoin

Bitcoin’s Energy Problem - electronic waste



https://en.wikipedia.org/wiki/Environmental_impact_of_bitcoin

Bitcoin’s Energy Problem - “digital crude”

Between 2016-2021:

- **per coin climate damages** from BTC were **increasing**, rather than decreasing as the industry matured
- during certain time periods, BTC climate **damages exceed the price of each coin** created
- on average, each **$1 in BTC market value** created was responsible for **$0.35 in global climate damages**
  - between beef production and crude oil burned as gasoline
  - an order-of-magnitude higher than wind and solar power

Benjamin A. Jones, Andrew L. Goodkind & Robert P. Berrens. Economic estimation of Bitcoin mining’s climate damages demonstrates closer resemblance to digital crude than digital gold (2022)

Proof-of-Stake (PoS)

Nakamoto Design

- Blocks are arranged on a chain (tree)
- Each block points to the predecessor
- In case of conflicts, we pick the longest chain (the hardest to generate)

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- Each block points to the predecessor
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- New blocks are generated by who wins the lottery
  1. PoW: computational lottery
     - Probability of winning proportional to computational power
     - Security as long as the majority of computational power is in the hand of honest parties
  2. PoS: lottery based on stake
     - Probability of winning proportional to stake (=amount of cryptocurrency on your account)
     - Security as long as the majority of cryptocurrency is controlled by the honest parties
     - Idea: who is winning the (economy) game is more incentivised to keep it running

The time slot

- Time is continuous
- Protocol breaks time in **slots**
  - Defines a “slot length” parameter (in seconds)
- Slot **large enough**
  - E.g., if network is assumed synchronous, slot length depends on graph’s diameter, s.t. all parties receive a message within a time slot
- Slot **not too large**
  - Otherwise protocol is slow
  - E.g., in Bitcoin waiting until tx is published is 10 mins (until a block is created) or more (for safety, k blocks are needed)
- Parties act based on the time slot they are in
  - Requires synchronized clock

Proof-of-Stake (PoS)

- **Sybil resilience** depends on "**stake**"
  - Stake: the amount of digital assets (tokens) a party controls
  - Akin to computational power in PoW, but stake is **digital**
  - **Energy efficient**: no need to consume high amounts of energy to run the stake-based lottery
- Parties produce blocks **proportionally** to the stake they control
  - Smallest rate: linearly proportional
- Assumption: **Adversary does not control a stake majority**
  - Corrupted parties control, on aggregate, less stake than the honest parties

Two broad categories:

- Nakamoto-style
- BFT-style

From PoW to PoS, Nakamoto style

The setting:

- The number of all assets is known
  - Tokens are recorded on the ledger
- The public key that controls each asset is known
  - Stake transfers (e.g., payments) are recorded on the ledger
- One block should be created per slot

High level idea:

- At each slot, choose one of the assets *at random*
  - Relaxation: choose a *very small* number of assets at random
- The owner of the chosen asset is eligible to produce a block at that slot
  - Owner: the person with the private key that owns the asset

PoS setting

- Assume (for now) that stake does not change hands
  - There are no changes in stake ownership
  - The initial set of stake owners is known (e.g., hardcoded in the genesis block)
- Let n be a node
  - vk_n: the public key of n
  - $stake_n$: the stake owned by n
  - Both vk_n and $stake_n$ are known by all parties

Recall PoW

$$H(x, s, ctr) < T$$

- H: hash function
- ctr: PoW counter
- x: MTR of block’s transactions
- s: hash of previous block’s header
- T: difficulty threshold

From PoW to PoS - Attempt 1

- Require: $H(x, s, vk_n) < T \cdot stake_n$
    1. threshold is proportional to stake of each party (right side of inequality)

From PoW to PoS - Attempt 1

- Require: $H(x, s, vk_n) < T \cdot \text{stake-factor}_n$
    1. threshold is proportional to stake of each party (right side of inequality)

Grinding Attack on x:

- Attacker can try different x's (e.g., transaction MTRs) to find one that satisfies the inequality

From PoW to PoS - Attempt 2

- Require: $H(s, vk_n) < T \cdot \text{stake-factor}_n$
  1. threshold is proportional to stake of each party (right side of inequality)
  2. inequality's left side does not depend on input x (to prevent grinding)

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Content Malleability:

- Block's content (transactions) not represented in the header anymore → Attacker can alter the previous blocks' transactions without altering the headers (which are validated in the PoS mechanism)

From PoW to PoS - Attempt 3

- Require: $H(s, vk_n) < T \cdot \text{stake-factor}_n$
  1. threshold is proportional to stake of each party (right side of inequality)
  2. inequality's left side does not depend on input x (to prevent grinding)
  3. Use the signing key for vk_n to sign x and a hash of all history (to prevent content malleability)

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Posterior Corruptions:

- Attacker can corrupt parties *after the slot passes* when they create a block → Attacker can change part (or all) of the chain's history (costless simulation)

From PoW to PoS - Attempt 4

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  4. Key Evolving Signatures (KES) (to prevent posterior corruptions)
     - Parties refresh their keys continuously (delete old keys, create new keys linked with old ones)

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Adaptive attack:

- vk that satisfies inequality is publicly known *before* the time slot starts → Attacker can predict the slot "leader schedule" → Can corrupt a party that is known to be leader of a specific future slot

From PoW to PoS - Attempt 5

- Require: $\mathrm{VRF}(sk_n, s) < T \cdot \text{stake-factor}_n$
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  5. Verifiable Random Function (VRF) (to prevent adaptive corruptions)
     - Intuition: a party runs the inequality using its *secret* key
     - The VRF output is verifiable *publicly* (i.e., with the party's public key)

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Stalling Hazard:

- With some probability (depending on T), no vk will satisfy the equation → No block is created at that slot → No parameter in the inequality changes → The protocol stalls

From PoW to PoS - Attempt 6

- Require: $\mathrm{VRF}(sk_n, s \,||\, ts) < T \cdot \text{stake-factor}_n$
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     - Intuition: a party runs the inequality using its *secret* key
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  6. ts (e.g., timestamp) changes as slots change (to prevent stalling)

Dynamic Stake

- **Stake changes hands** via payments/transfers
  - New stakeholders (i.e., keys) are added
  - The stake of old stakeholders is reduced
- Stake ownership distribution **depends on the chain** (i.e., branch)
  - Different blocks (in different chains) will contain different transactions

Key Grinding Attack

- Each user’s key is created locally (by the user)
- Creating keys is (effectively) costless
- The adversary may be able to play multiple possible VRF calculations “in its head” prior to committing to a particular key.

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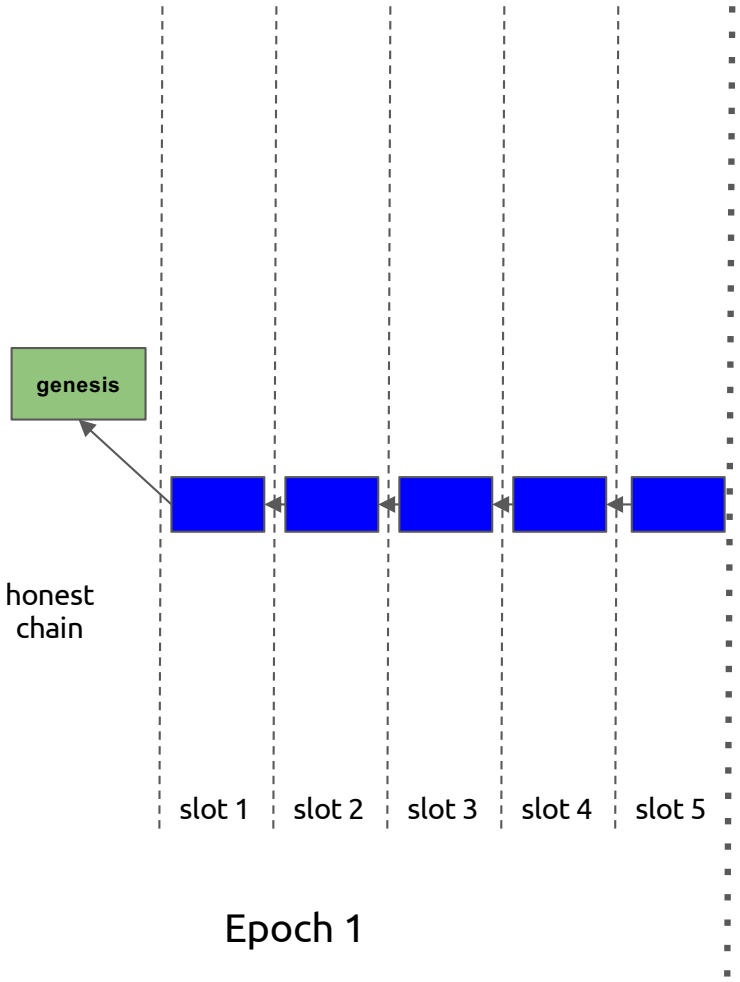
Solutions:

- Have all parties commit to their keys
- Generate randomness to include into the VRF calculation.
  - Key point: hashing a prior VRF value sequence may suffice!
- Time is divided into epochs: each epoch has its own stakeholder distribution and randomness.

Long-range attack



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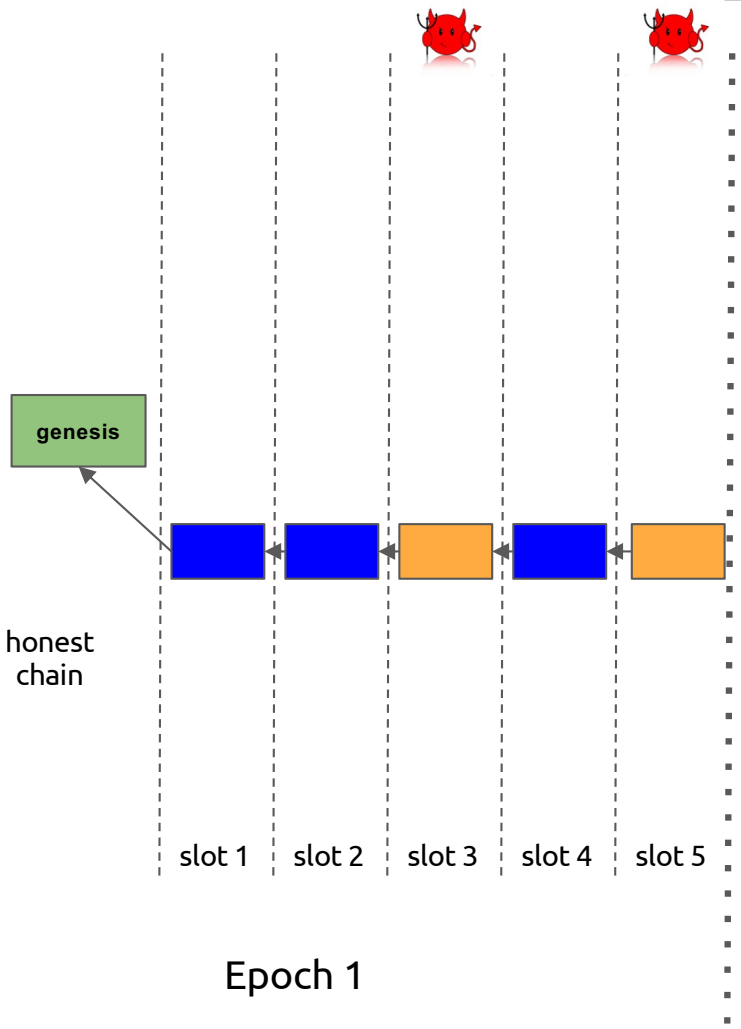

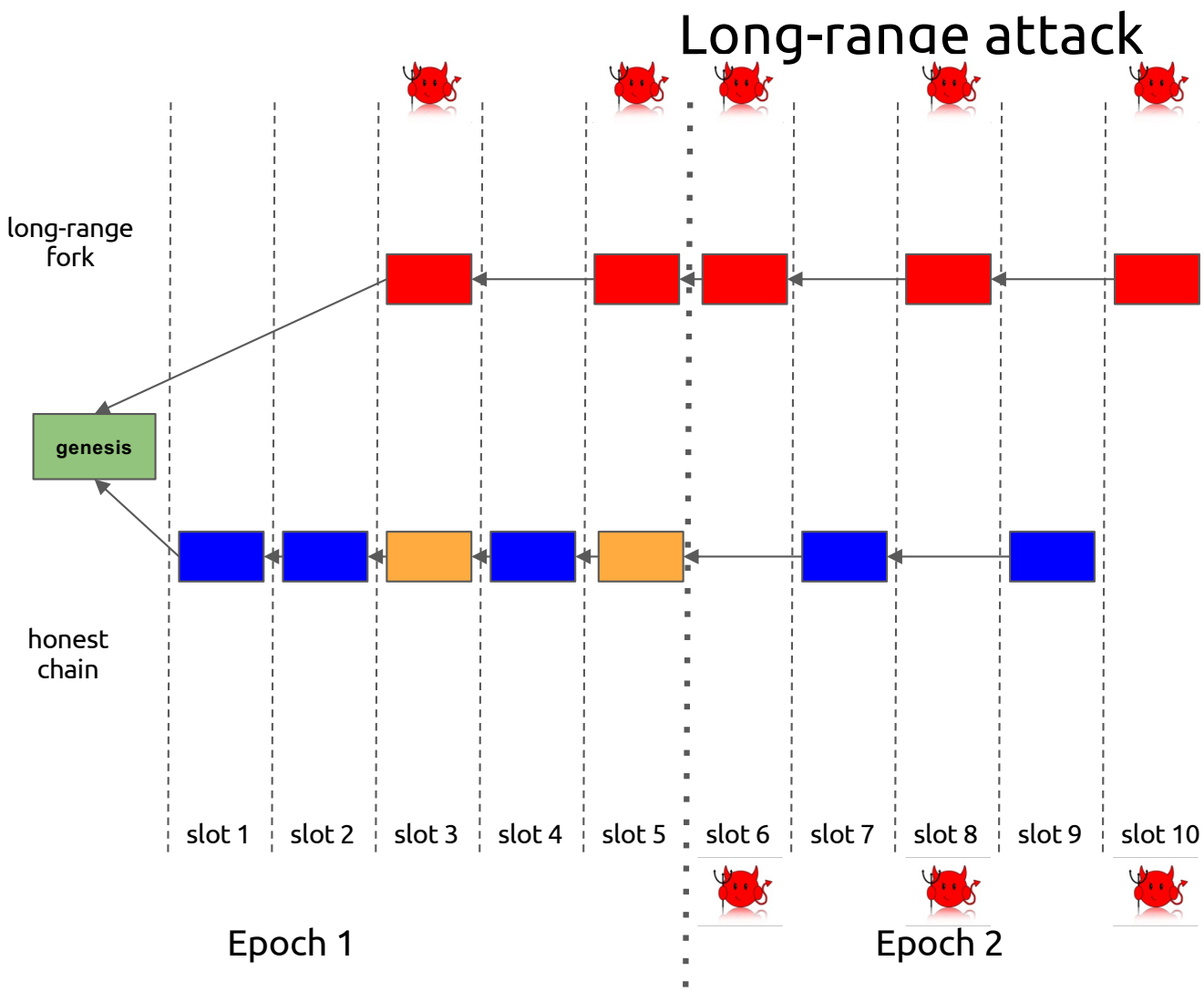
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honest
chain
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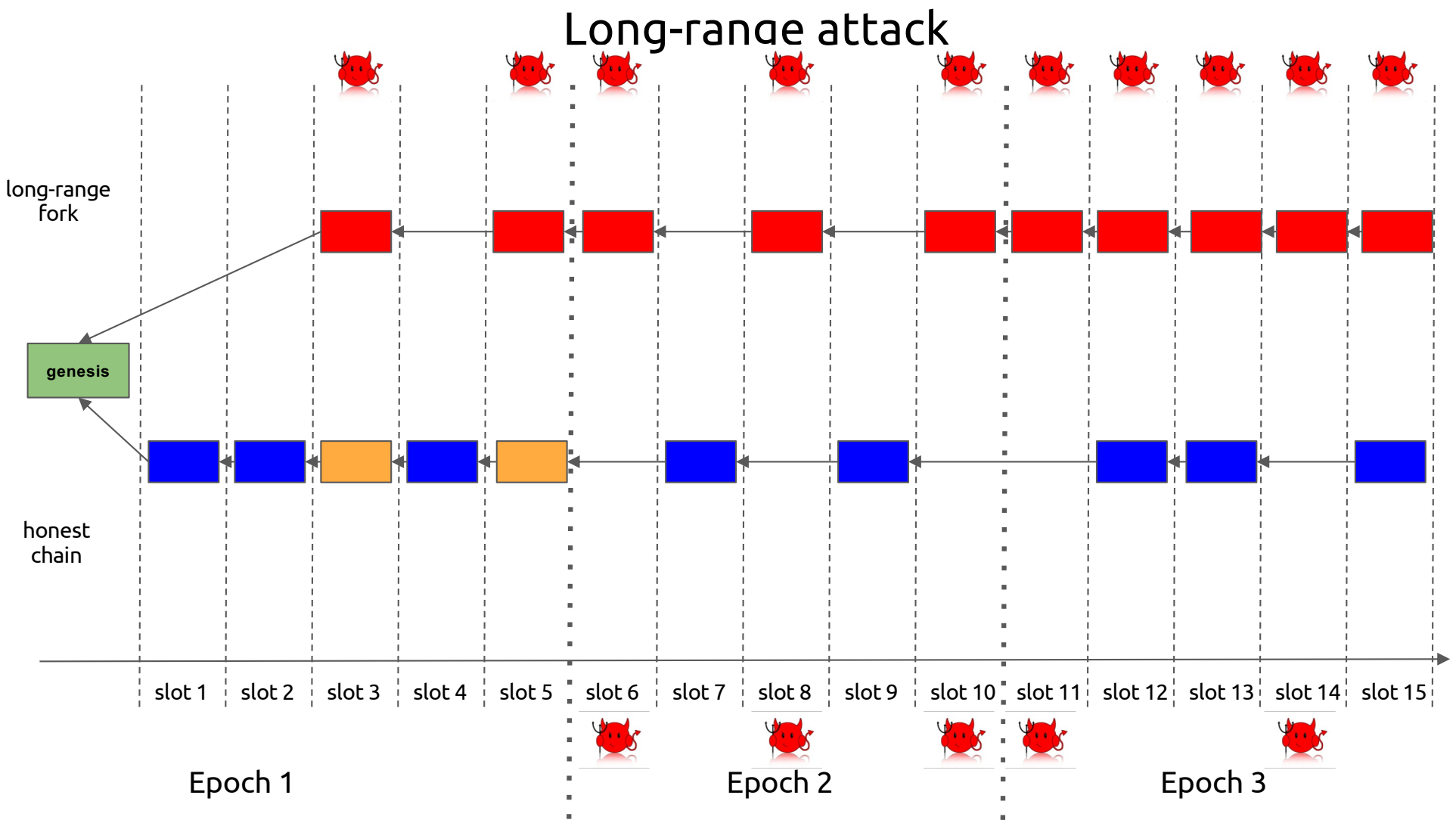
Epoch 1
Epoch 2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Epoch 3

Long-range attack

- The attack:
  - Starting from an old block, the attacker creates a chain of adversarial-only blocks
  - In this chain, it collects the rewards for every block
    - In this branch/“fork”, the attacker’s stake is increased
  - After some point, the attacker gets stake majority in this fork
  - Because of costless simulation, the attacker can create an arbitrarily long chain in “its head”
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- Solution#1: checkpointing
  - Joining parties receive trusted checkpoint

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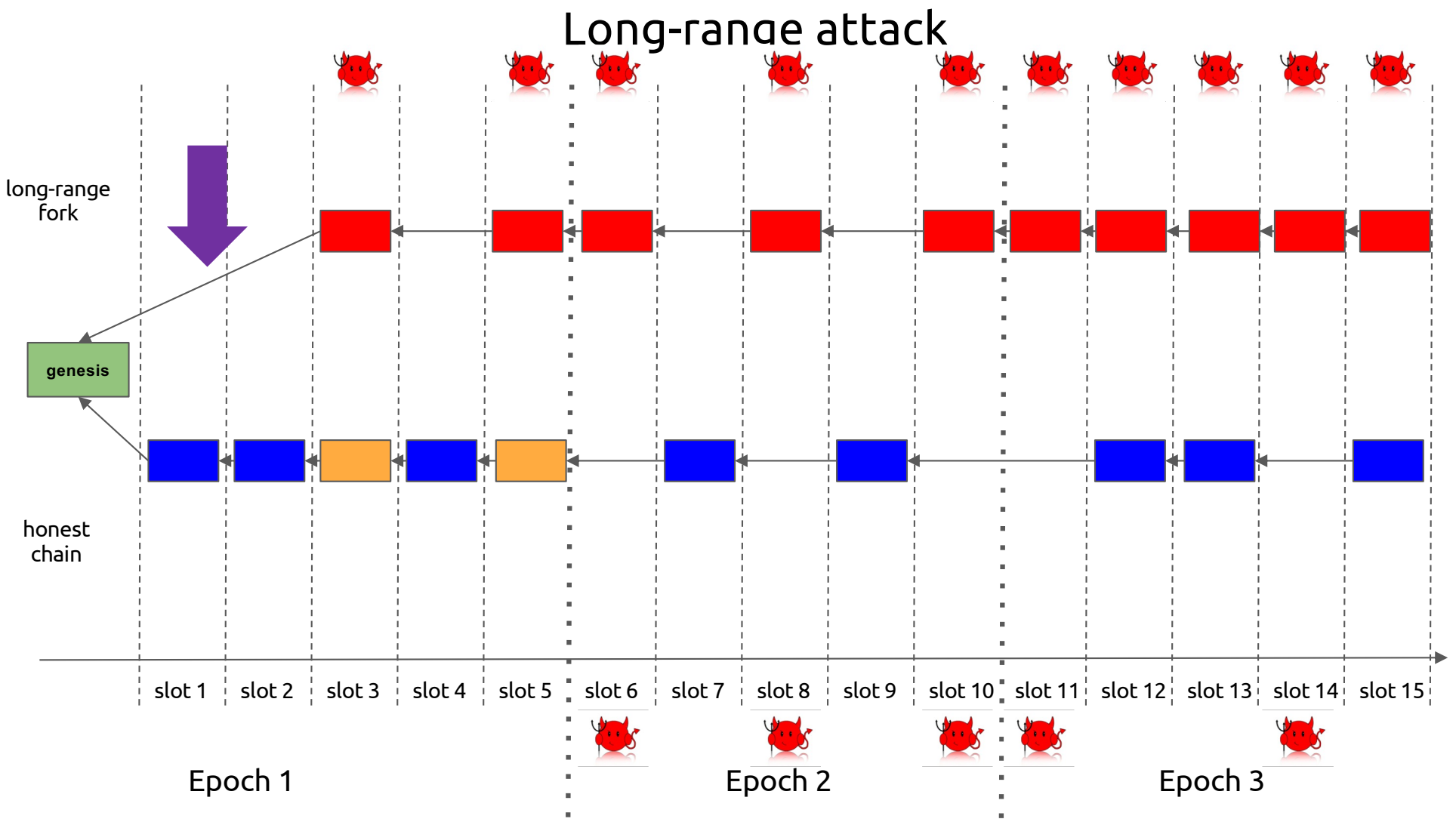
- Solution#1: checkpointing
- Solution#2: chain density
  - Basic idea: **immediately after the fork**, the **honest** chain’s blocks are **more “dense”** compared to the attacker’s (forked) chain
  - A new node that joins the system, chooses a path at each fork by following the most dense branch
  - The idea behind Ouroboros Genesis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Permissioned Ledgers

Permissioned Protocols

- Participation is **restricted**:
  - Producing transactions and/or blocks can only be performed after being authorized by (some) other nodes
- In the simplest case, the set of nodes is **static**:
  - the set of participating nodes is fixed and determined at the onset of protocol's execution

Permissioning How-To

- Most straightforward approach:
  - employ a PKI (Public-Key Infrastructure)
- Use digital signatures / authentication protocols
- **Certificate authorities** can authorize other entities
  - authorization includes a signature from the CA on the entity's public-key, identity info etc
  - example: TLS/SSL
- Sharing certificate authority information is necessary
  - All computer systems come with preloaded certificates from certificate authorities - a **setup assumption**
- Certificates need to be **revoked** in case the corresponding secret keys become exposed or the algorithms used are not safe anymore

X.509 Certificates

- Internet standard since 1988
  - http://www.ietf.org/rfc/rfc3280.txt
- Hierarchical

Version
Serial Number
Algorithm / Parameters
Issuer
Period of Validity: not before date not after date
Subject
Algorithm/ Parameters/ Key
x509v3 extensions
...
Signature

X.509
does not
specify
cryptographic
algorithms

Digital Signatures and Certificates

- A certificate contains a digital signature
- Cryptographic design of digital signatures involves typically:
  - A cryptographic signing operation that acts on a fixed input of a specific type and has a public-verifiability feature
  - A cryptographic hash function that takes arbitrary strings and maps them to the data type suitable for the signing operation
  - Common setting today: SHA2 with RSA or DSA

Secure channels and certificates

- Possession of mutually acceptable certificates:
  - permits authenticated communication (exchanging signed mechanism between two entities)
  - allows building a secure channel
- *TLS 1.3* can be used to build such secure channel:
  - Based on cryptographic protocols like Diffie-Hellman key exchange
  - Data confidentiality ensured

Static Permissioned Ledger

- Prior to system's start:
  - the nodes register their certificates
  - these certificates are included in the genesis block
- Using these certificates, all nodes are capable of:
  - authenticating each participant
  - allowing interaction with the shared state, in a way prescribed by the participants' credentials
- The set of participants remains the same throughout the execution
- This is the simplest form of a PKI / public-key directory
- [Compare this to PoS protocols]

A Centralised Permissioned Ledger

- Assume just a “LOG” of transactions
- **One of the participants** acts as a server and maintains the LOG
- Readers and writers to the LOG authenticate with the server and can perform read and write operations
- Consistency of the LOG is guaranteed, assuming the **server is trusted**
- Liveness of the LOG is guaranteed, assuming the server is **trusted and functional**
- If server is corrupted, the ledger is compromised
- Sometimes referred to as Proof of Authority, PoA

Comparison to Bitcoin's Permissionless Ledger

- The genesis block contains no certificate information
- **Reading** from the LOG is **open**
  - anyone can do it, without credentials
- Writing to the LOG requires a specific type of credentials
  - write: insert data into the log
  - Nodes can obtain valid credentials (accounts) by generating a public and secret-key and:
    - mine a block (and be rewarded with BTC) or
    - buy BTC from another node
- Once the LOG records their account credit, they can issue transactions (and pay the necessary fees)
- In essence: crediting a bitcoin account is akin to creating a certificate that imparts the account holder with certain permissions w.r.t. the ledger

Distributed Permissioned Ledger

- A **number of servers** maintain the ledger (LOG) individually
- All share the **same genesis block** that identifies all participants
- Assuming a synchronous operation, at each round, readers and writers:
  - authenticate with the servers
  - interact with the LOG in a prescribed fashion

Distributed Permissioned Ledger

- A **number of servers** maintain the ledger (LOG) individually
- All share the **same genesis block** that identifies all participants
- Assuming a synchronous operation, at each round, readers and writers:
  - authenticate with the servers
  - interact with the LOG in a prescribed fashion
- Readers authenticate to each server and obtain read access
- Writers authenticate to each server and provide their inputs
- Servers run a **consensus protocol** to agree what inputs should be included in the LOG

Read Requests

- Is it possible to restrict read requests, as in the centralized setting?
  - Hint: Nodes keep blocks of transactions private and issue them only to authenticated users
- TLS can be used to build a secure channel between the reader and the responding node
- Requirement that all servers remain honest (as they all share the LOG)
- Is is possible to impose read restrictions on servers as well?
  - Hint: Threshold encryption

Reader/Writer Management

- Readers and writers can authenticate to each server referring to the information in the genesis block
- It is possible to introduce additional readers and writers by suitably issuing certificates to other users
- Note that each participant would then need to show a valid certificate chain, that establishes their privileges for the requested read or write access

BFT Protocol Example

“Classical” BFT Consensus (example)

- Focus on write requests: we want to ensure LOG liveness and consistency
- We will build a “byzantine fault tolerant” (BFT) agreement protocol that uses two important tools:
  - a graded broadcast
  - a binary consensus protocol

Graded Consensus

- Parties involved :
  - a single **sender**
  - several receivers
- The i-th receiver outputs (M_i, G_i)
  - M_i: the output message
  - $G_i \in \{0, 1, 2\}$: the grade of the message

Properties

- If the sender is **honest**, then $M_i = M_j$ for all i, j and $G_i = 2$
- If the sender is **malicious** and one receiver outputs (M, 2), then all other honest receivers output (M, G_i) with $G_i \in \{1, 2\}$

Graded Broadcast Protocol

Communication

- **Round 1.** The sender sends the message M to all receivers
- **Round 2.** The i-th receiver, who obtained $M_{1,i}$ in round 1, sends it to all receivers
- **Round 3.** The i-th receiver, who obtained $M_{2,j,i}$ from the j-th receiver in round 2:
  - if there is a single message that was sent by at least $2n/3$ receivers, it sends it to all receivers
  - else does nothing

Graded Broadcast Protocol

Communication rounds

1. The sender sends the message M to all receivers
2. The i-th receiver, who obtained $M_{1,i}$ in round 1, sends it to all receivers
3. The i-th receiver, who obtained $M_{2,j,i}$ from the j-th receiver in round 2:
    - if there is a single message that was sent by at least $2n/3$ receivers, it sends it to all receivers
    - else does nothing

Output Generation

The honest i-th receiver does the following:

- If a single message was received from *at least* $2n/3$ receivers in round 3, output that message as M_i and set $G_i = 2$
- If a single message was received from *at least* $n/3$ receivers in round 3, output that message as M_i and set $G_i = 1$
- In any other case, output *fail* as M_i and set $G_i = 0$

Graded Broadcast Protocol (Analysis: t < n/3)

Theorem #1

If the sender is honest and broadcasts *M*, then all *honest* receivers P_i will output $G_i = 2$ and *M* in the output generation stage.

Proof

- If the sender is honest, then all honest receivers will receive the same message *M* in round 1.
- Since t < n/3, each receiver will receive *M at least* 2n/3 times in rounds 2 and 3 (from the honest parties).

Communication rounds

1. The sender sends the message *M* to all receivers
2. The *i*-th receiver, who obtained $M_{1,i}$ in round 1, sends it to all receivers
3. The *i*-th receiver, who obtained $M_{2,j,i}$ from the *j*-th receiver in round 2:
    - if a single message was sent by at least *2n/3* receivers, send it to all receivers

Output Generation

The honest *i*-th receiver:

- If a single message was received from *at least 2n/3* receivers in round 3, outputs that message as M_i and set $G_i = 2$

Graded Broadcast Protocol (Analysis: t < n/3)

Lemma #1

If two honest receivers send a message in round 3, it *must be* the same.

Proof

Suppose an honest party P sends message *M* in round 3:

1. P has received *M* by at least 2n/3 parties in round 2 *(by definition)*
2. Let **h** be the number of *honest parties* that sent *M* in round 2: h ≥ (2n/3) - t > n/3 *(by assumption)*
3. Let **p** be the parties *capable* of sending a *different* message *M' ≠ M* in round 2: p = n - h < 2n/3 *(by step 2, i.e., since h honest parties sent M)*
4. Therefore, any other honest party in round 3 will send *M* or do nothing

Communication rounds

1. The sender sends the message *M* to all receivers
2. The *i*-th receiver, who obtained $M_{1,i}$ in round 1, sends it to all receivers
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Graded Broadcast Protocol (Analysis: t < n/3)

Theorem #2

Suppose the i-th receiver returns $G_i = 2$ and a message M_i; for the j-th honest receiver's output (M_j, G_j), it holds $M_i = M_j$, $G_j \in \{1, 2\}$.

Proof

First, we show that it cannot be that M_j = *fail*:

1. The i-th party received M_i from at least 2n/3 receivers in round 3 (of which at most t<n/3 adversarial)
2. So, *more than* n/3 *honest* parties sent M_i in round 3

Now, suppose $M_j \neq M_i$:

1. M_j was sent by at least n/3 receivers in round 3 *(by definition)*
2. At least one of them is honest *(since t < n/3)*
3. By Lemma #1, it holds $M_i = M_j$ [*contradiction*]

Communication

Round 3. The *i*-th receiver, who obtained $M_{2,j,i}$ from the *j*-th receiver in round 2:

- if a single message was sent by at least *2n/3* receivers, send it to all receivers

Output Generation

The honest *i*-th receiver:

- If a single message was received from *at least 2n/3* receivers in round 3, outputs that message as M_i and set $G_i = 2$
- If a single message was received from at least n/3 receivers in round 3, output that message as M_i and set $G_i = 1$
- In any other case, output *fail* as M_i and set $G_i = 0$

From Graded Broadcast to a BFT-Ledger

If grade $G_i = 2$, party P_i knows that other honest parties have received M_i

Graded broadcast *is not enough*:

- If grade $G_i = 1$, party P_i cannot know if other honest parties received the message

Solution:
Perform binary consensus to detect whether everyone has grade 2 or not.

From Graded Broadcast to a BFT-Ledger

A simple approach:

- execute n/3 phases (to guarantee at least one honest sender encountered)
- in each phase:
  - A designated sender organizes all valid transactions as *M* and performs a graded broadcast
  - A binary consensus protocol determines whether everyone's grade is 2 or not:
    - If true, each node signs the output to generate a public endorsement and appends *M* to their LOG (together with the signatures)
    - otherwise, LOG remains the same

Byzantine Binary Consensus

- (RECALL) n parties, t adversarial
- $v_i \in \{0, 1\}$ the input of party i
- Honest parties should *decide* on values $u_i \in \{0, 1\}$ satisfying the following properties:
  - **Termination**: values u_i are well defined for all honest parties
  - **Agreement**: if parties i and j are honest, then $u_i = u_j$
  - **Validity**: if, for every honest party i, there exists $v \in \{0, 1\}$ such that $v_i = v$, then each honest party i outputs $u_i = v$

Note: We examine the *synchronous* setting

Exponential Information Gathering Algorithm (EIG)

Algorithm Sketch:

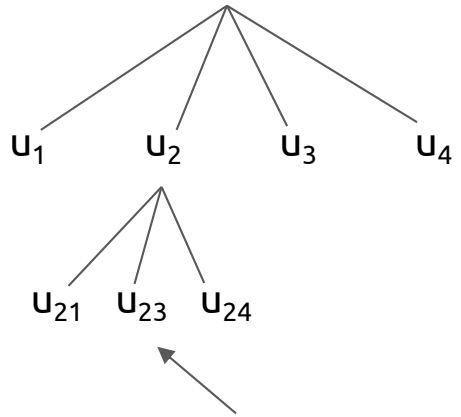
- At round 1, send everyone your input
- At round r+1, send everyone all messages you received at round r (avoiding redundant messages – see below)

Each party arranges the messages in its own EIG tree:

- Let $u_1,...,u_n$ be the messages received in the first round (including own message)
- $u_{i1i2...ik}$ is a value v s.t. *(i_k told i) that (i_{k-1} told i_k) that … that (i_1 told i_2)* that i_1's initial value was v

  we want i1,…,ik to be all distinct

(Food for thought) What is the size of the tree?



u_{23}: The value party 3 told me that party 2 sent them in the previous round.

EIG Termination

The EIG algorithm terminates after t+1 rounds. The output value of each party is defined as follows:

- For each leaf v in the EIG tree, set $z_v=u_v$
- For an internal node v, set z_v equal to the majority of the z-values of its children; if the majority is not defined, set $z_v=0$ (without loss of generality)
- Define the output as z_{root}

(Food for thought) Prove that EIG satisfies: i) agreement; ii) validity. (Hint)

Impossibility results - asynchronous setting

- *Theorem [LSP1982]*: Impossible for n < 3t + 1.
- *Theorem [FL1982]*: Impossible in t rounds.
  - *Example:* The EIG algorithm with t = 1 needs at least 2 rounds:
    - If a party received a single 1, its output should be 0. (Because the 1 could be coming from the adversary.)
    - If a party received two 1s, its output should be 0. (Because one of them could have been sent from the adversary, while another party could have received a single 1 and will decide 0 according to the previous statement.)
    - And so on… (by induction, the output will always be 0, contradicting validity)
- *Theorem[GM1998]*: Doable for n > 3t in t + 1 rounds.
- *Theorem [DS83]*: Doable for n > 2t assuming a PKI.

Impossibility results - asynchronous setting

- *Theorem [BT1985]*: Asynchronous Byzantine Consensus is impossible with $n < 3t + 1$, even if the parties have agreed on a PKI (setup).
  - Partition parties into sets A, B, C of size at most t and consider 3 scenarios:
    i. A malicious, B and C honest with inputs 0. The adversary sends no messages. The honest parties should decide on 0 until some time T_A.
    ii. B malicious, A and C honest with inputs 1. The adversary sends no messages. The honest parties should decide on 1 until some time T_B.
    iii. C malicious, B and A honest with inputs 0 and 1 respectively. The adversary communicates with B as the honest C in scenario A and with A as the honest C in scenario B. At the same time every communication between A and B is delayed for time at least $\max\{T_A, T_B\}$.
  - The crux is that A has the same view in scenarios B and C. Similarly for B, in scenarios A and C. Agreement in scenario C is impossible, if validity is achieved in scenarios A and B.

Back to PoS

- … using ideas from BFT protocols

BFT-style PoS

High level idea:

- At each slot, subselect a committee of stakeholders
  - Getting elected to the committee is proportional to the party's owned stake
- The committee runs a BFT protocol to agree on the new block
- Each block is finalized per the BFT protocol rules
- The idea behind Algorand

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Some security considerations:

- Where does the randomness come from (for the committee selection)?
- How to prevent grinding attacks?
- How to prevent adaptive corruptions?
- How to prevent long-range attacks?

Food for thought in Ledger protocols

- How to ensure that parties have a synchronised clock?
  - How do parties coordinate in terms of the time progress?
  - How do parties agree on which time slot is active at any point in time?
  - Reference: Ouroboros Chronos (PoS-based), Permissionless Clock Synchronization (PoW-based)
- Will rational parties delete their keys?
  - Key erasures (in KES) are necessary to prevent posterior attacks.
  - Do parties get any benefit by not deleting their keys? Can an attacker incentivize this?
  - Can the protocol provide incentives (or counter incentives) to promote key erasure?
    - “economic security”
- What happens if an attacker gets a majority during one epoch?
  - Can the system recover from temporary adversarial majority?
  - Can PoW systems recover (without ”social consensus”)? What about PoS?
  - Reference: Self-healing blockchains