CS61065: Theory And Applications of Blockchain

# Consensus in Permissionless Settings

Department of Computer Science and Engineering

INDIAN INSTITUTE OF TECHNOLOGY KHARAGPUR

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# Permissionless Model

- Open network
  - Anyone can join in the network and initiate transactions
  - Participants are free to leave the network, and can join later again

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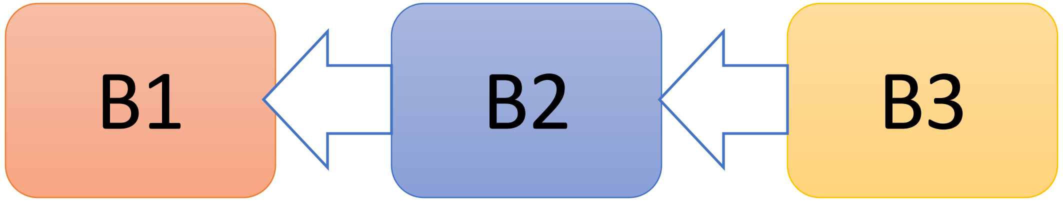
# Consensus in a Permissionless Model - Challenges

- Participants do not know others
    - Cannot use message passing !!

- Anyone can propose a new block
    - Who is going to add the next block in the blockchain?

- The network is asynchronous
    - We do not have any global clock
    - Theoretically, a node may see the blocks in different orders

# Consensus in a Permissionless Model - Challenges



B1

B2

B3

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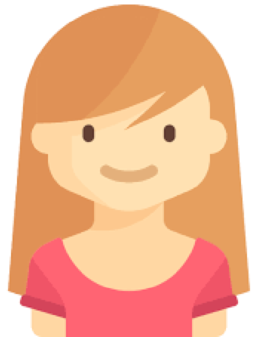

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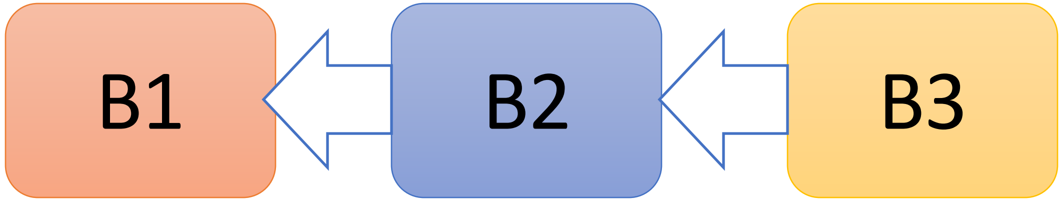

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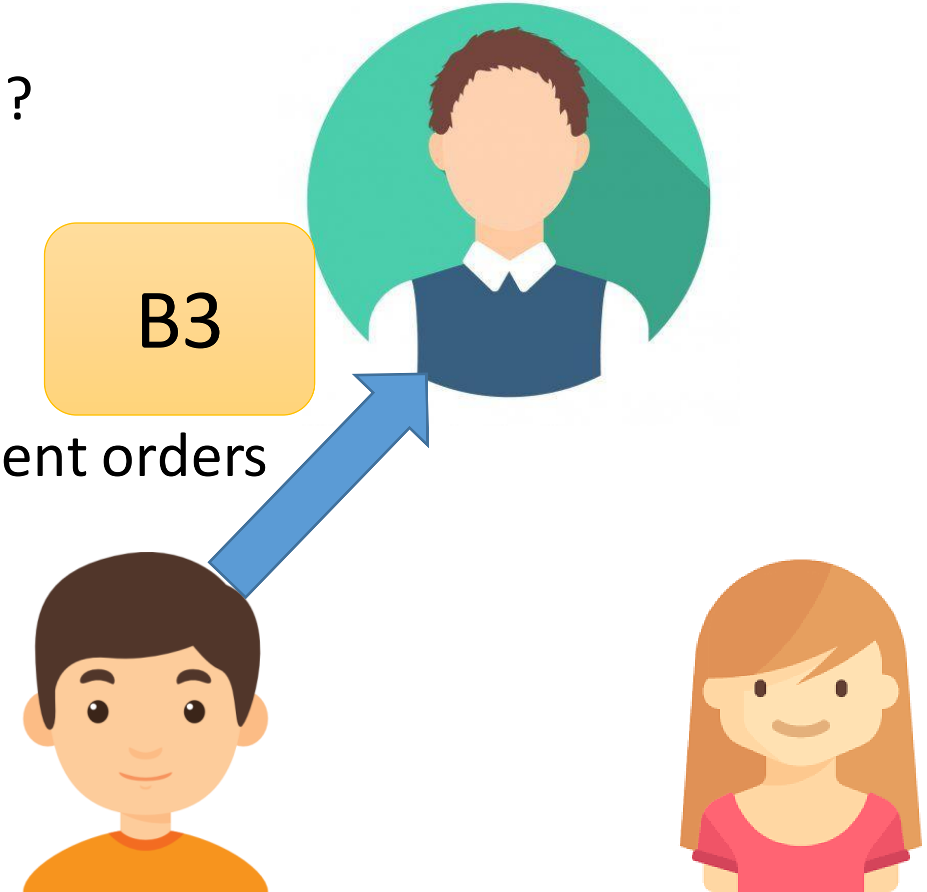

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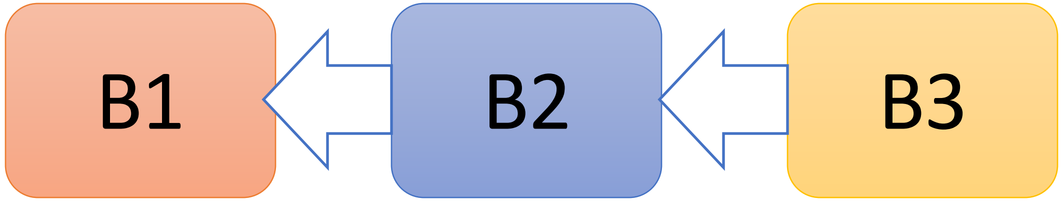

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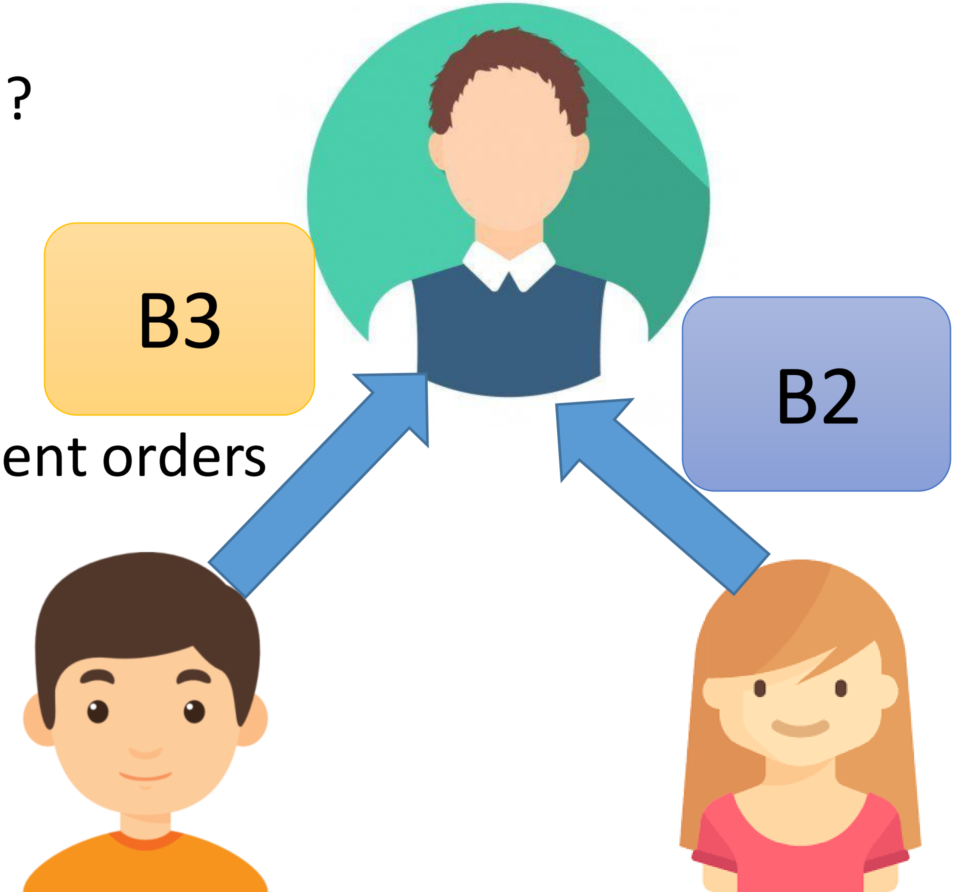

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  - Theoretically, a node may see the messages in different orders
- Any types of monopoly needs to be prevented
  - A single user or a group of users should not gain the control – we don't trust anyone

# Remember the FLP Impossibility?

- Synchronous vs Asynchronous Networks
  - **Synchronous**: I am sure that I'll get the message within a predefined time threshold
  - **Asynchronous**: I am not sure whether and when the message will arrive

- Failures in a network --
  - **Crash Fault**: A node stops responding
  - **Link Fault** (or Network Fault): A link fails to deliver the message
  - **Byzantine Fault**: A node starts behaving maliciously

- **The Impossibility Theorem**: Consensus is not possible in a perfect asynchronous network even with a single crash failure

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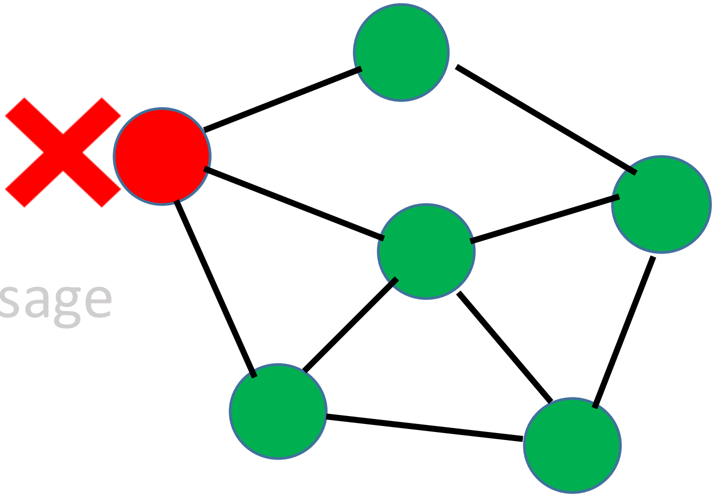

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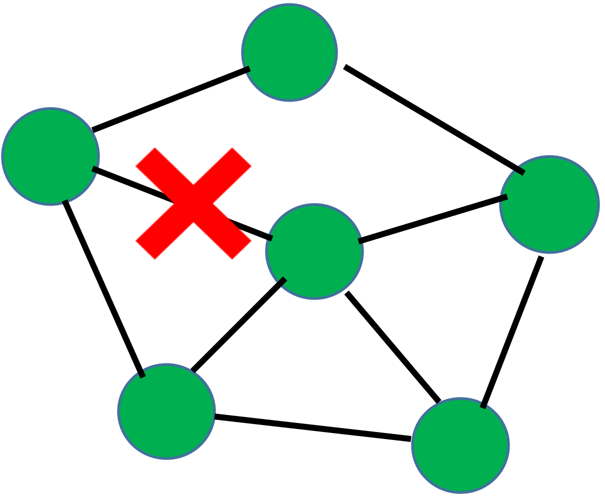

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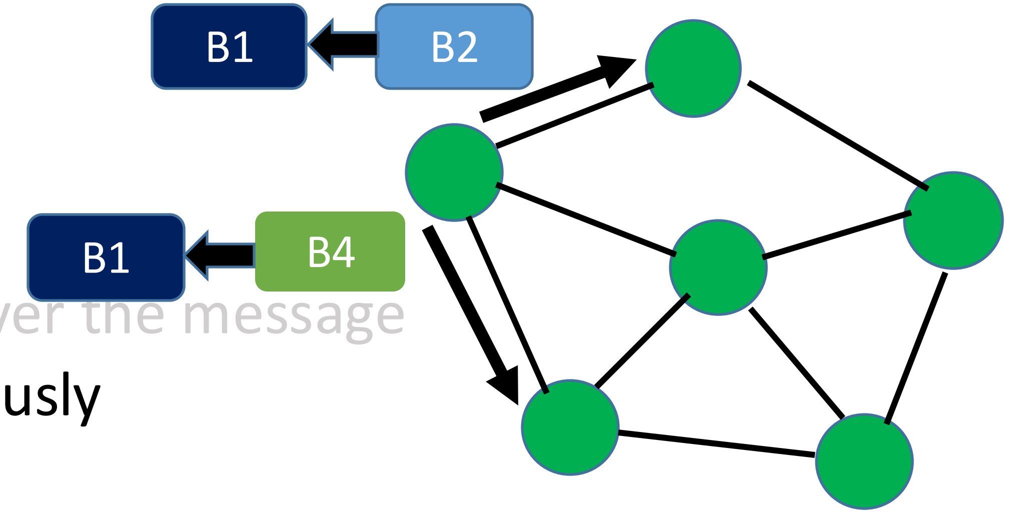

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  - Cannot ensure safety and liveness simultaneously

# Safety vs Liveness Dilemma

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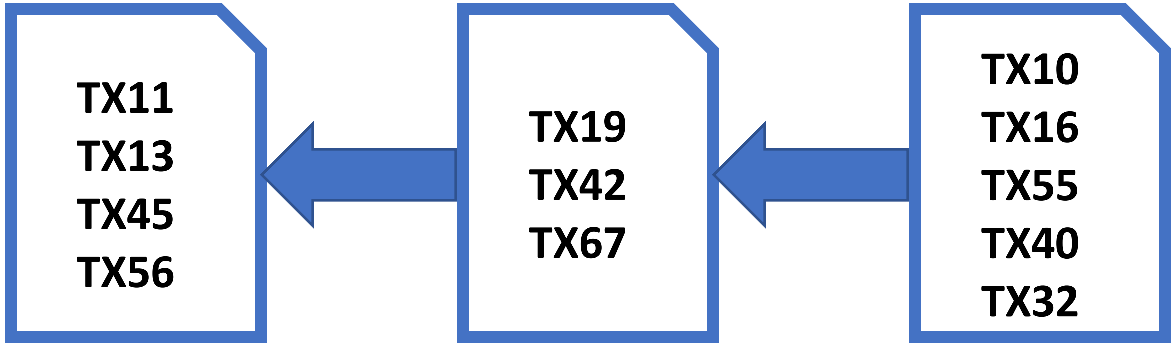
  - Cannot ensure safety and liveness simultaneously

**The Nakamoto Consensus (Proof of Work)**

**Liveness is more important than Safety**

**Immediate focus is on liveness with a minimum safety guarantee, full safety will be ensured eventually**

# Breaking the "Safety vs Liveness" Dilemma



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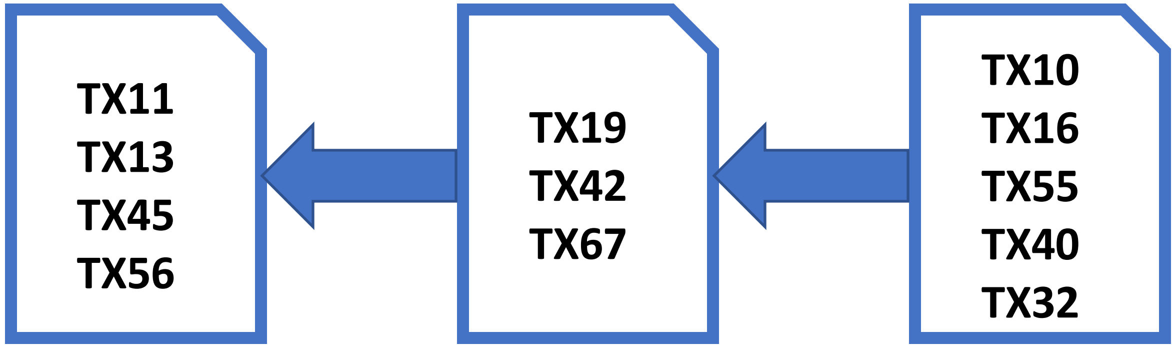

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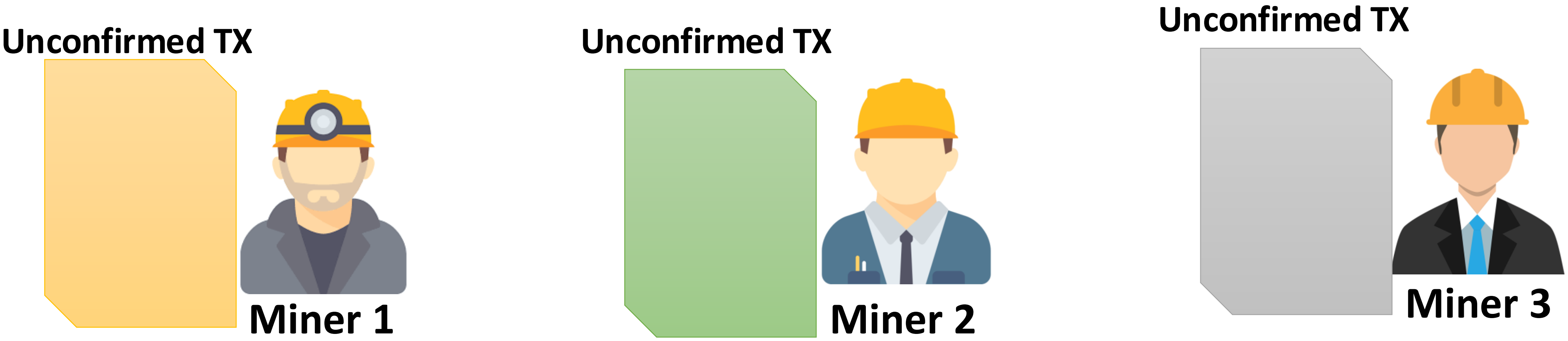
**Bitcoin Unconfirmed TX (mempool) :** https://www.blockchain.com/btc/unconfirmed-transactions



Unconfirmed TX

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Miner 3

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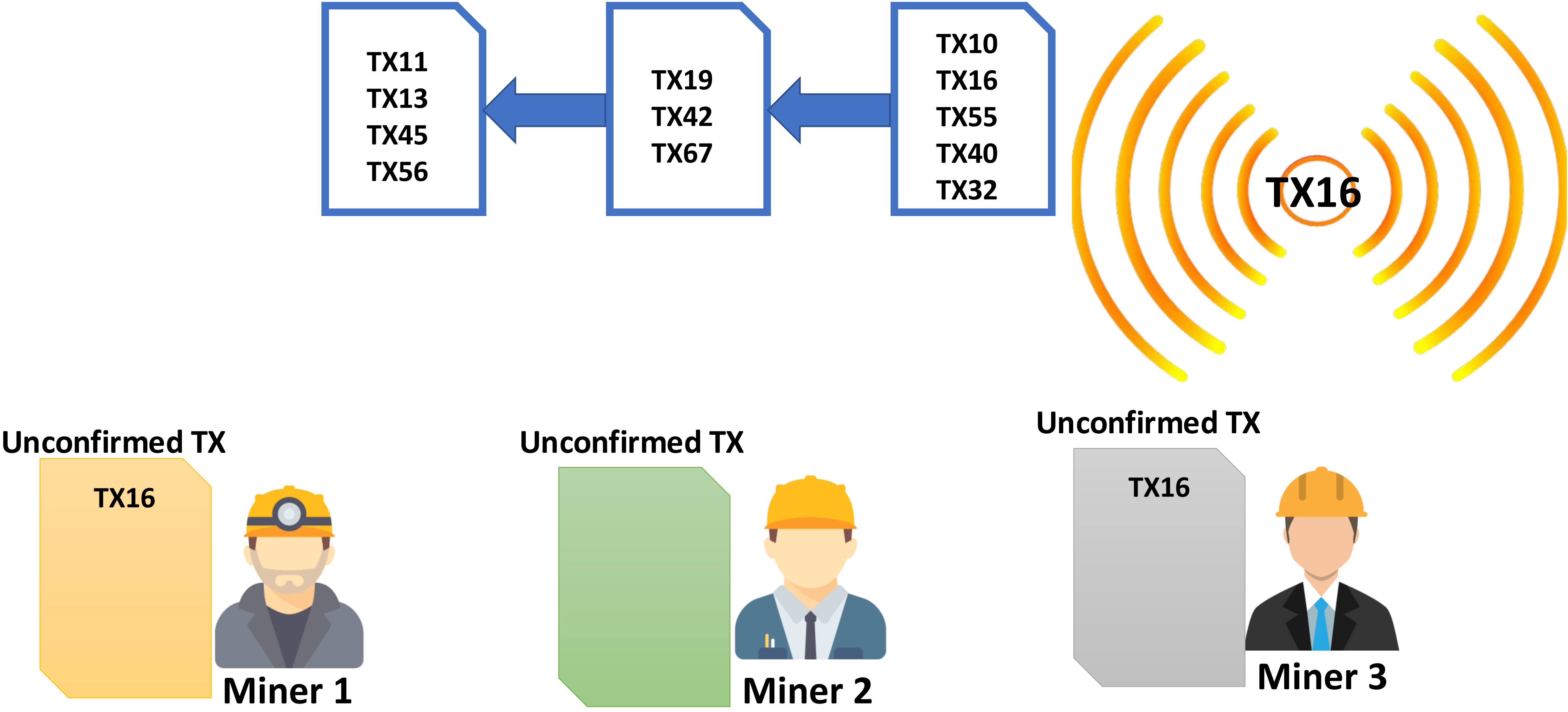

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Miner 3

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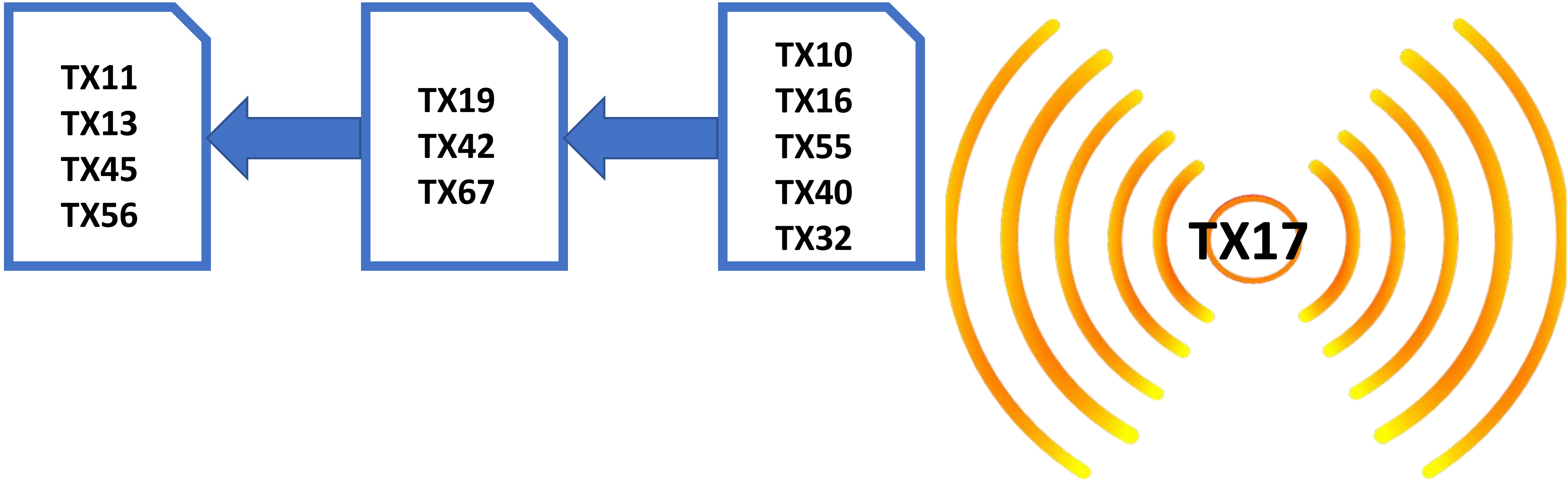

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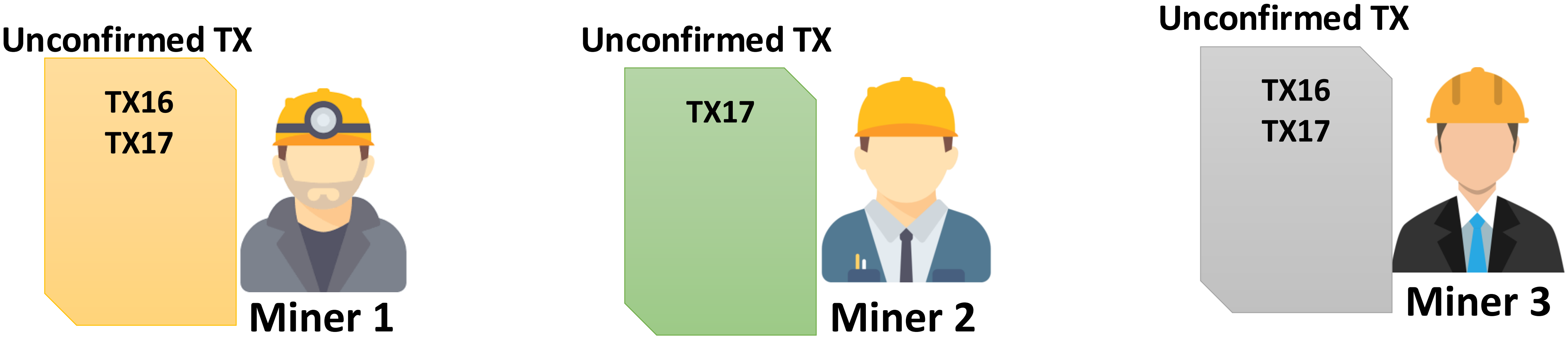

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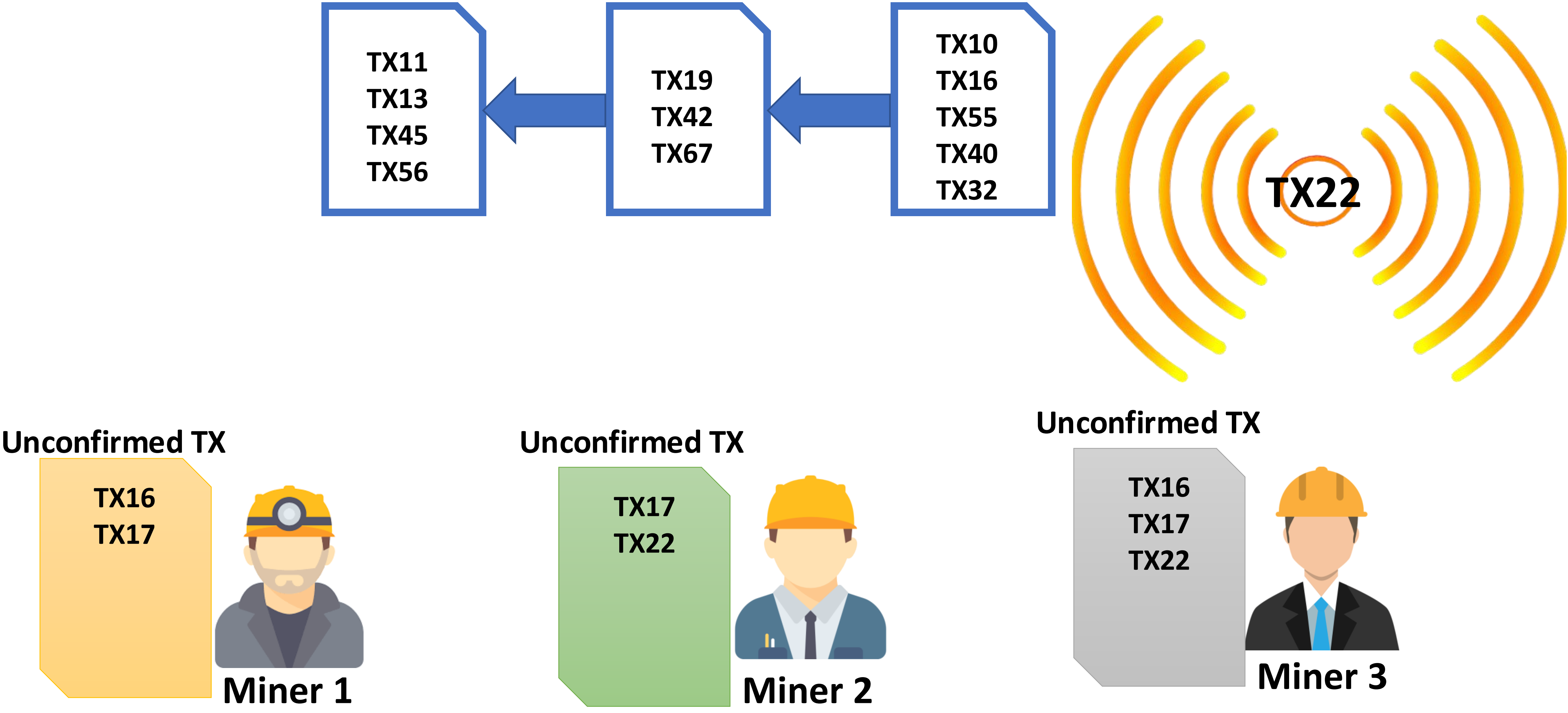

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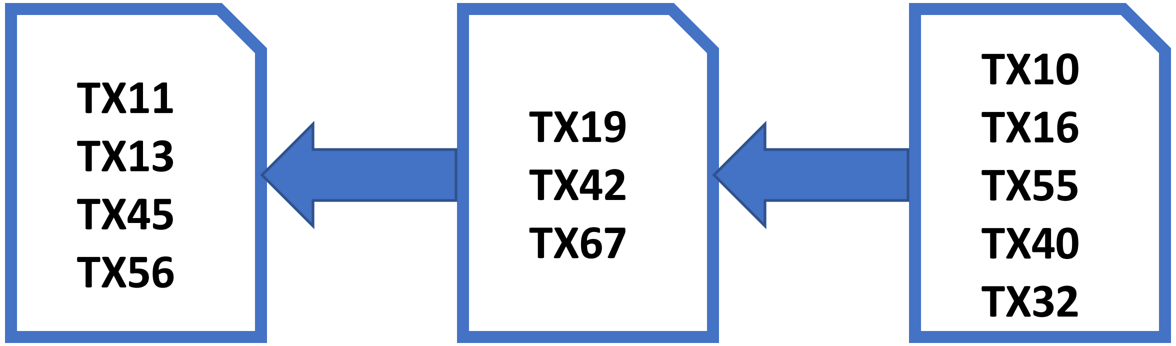

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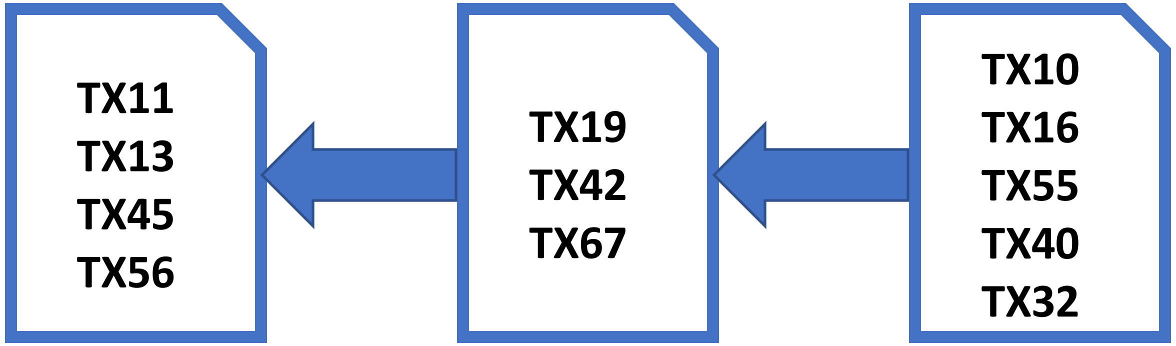

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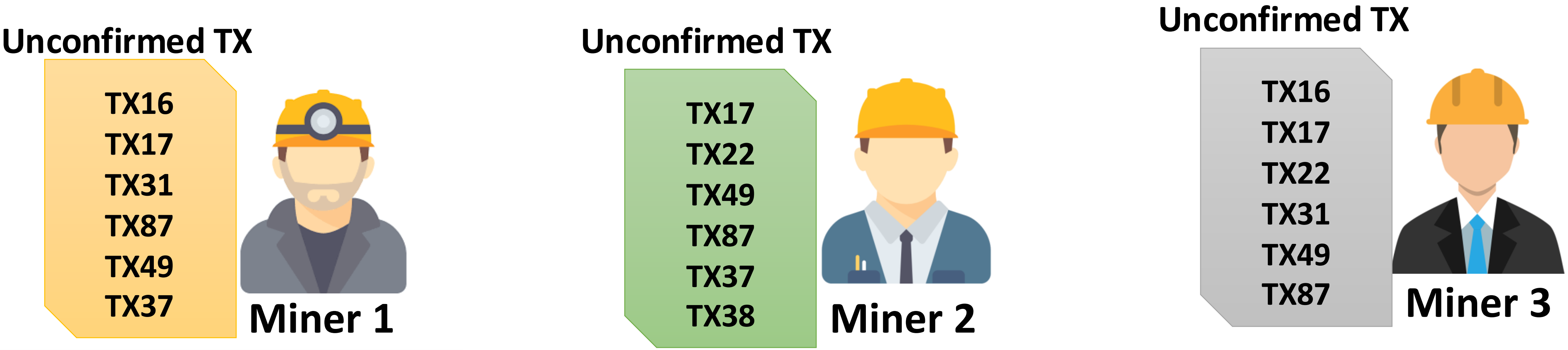
**Safety-1:** The next block should be "correct" in practice

- Transactions are verified, the block contains the correct Hash and Nonce



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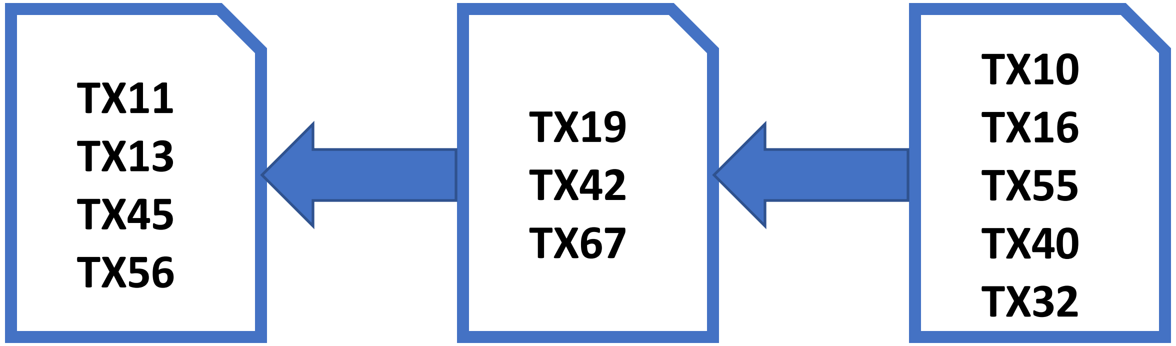

This can be ensured – the block mined by a miner is verified by all

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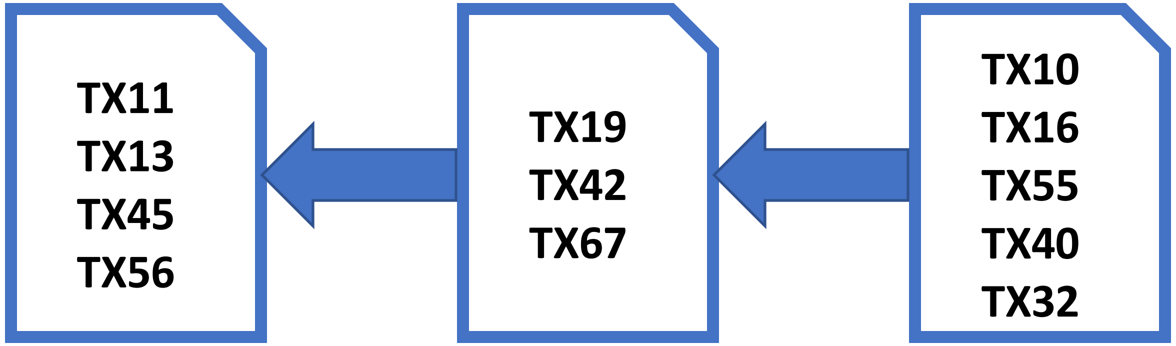

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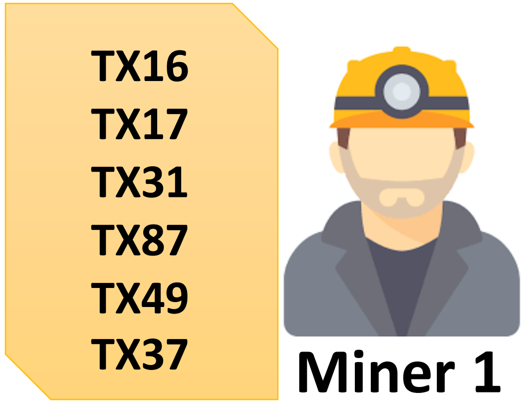
**Safety-2:** All the miners should agree on a single block

- The next block of the blockchain should be selected unanimously

Unconfirmed TX



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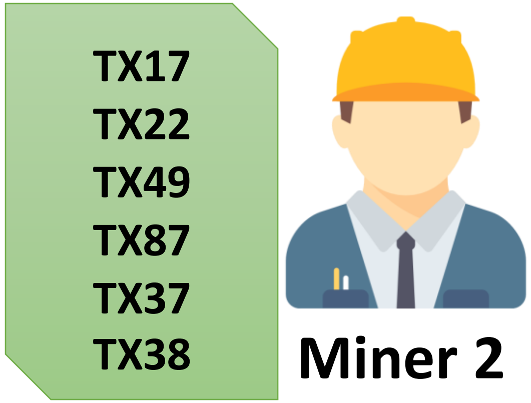

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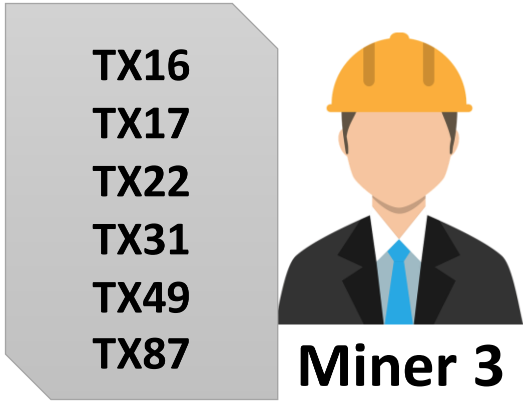
Miner 2

Unconfirmed TX



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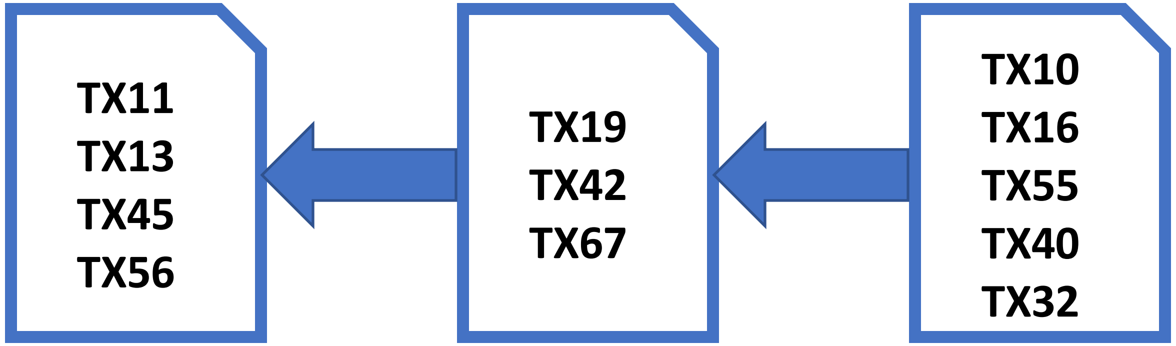

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Miners do not know each other – how can they agree on the same block?

**Safety-2:** All the miners should agree on a single block

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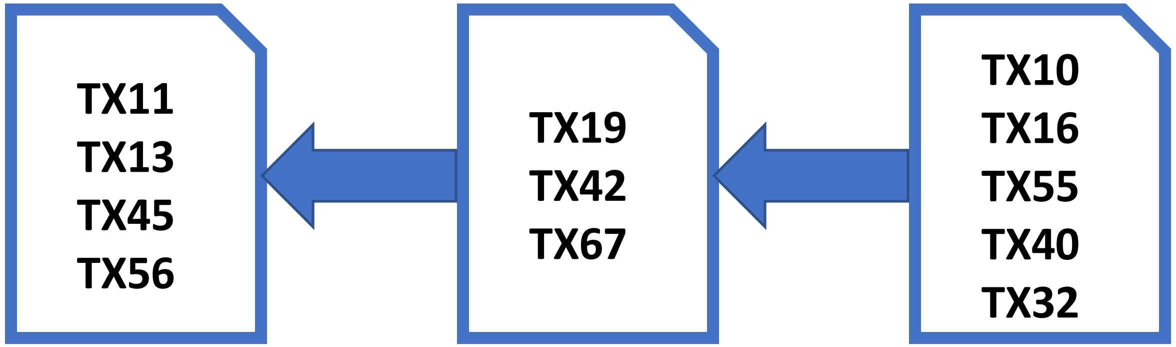

We compromise here!

**Safety-2:** All the miners should agree on a single block

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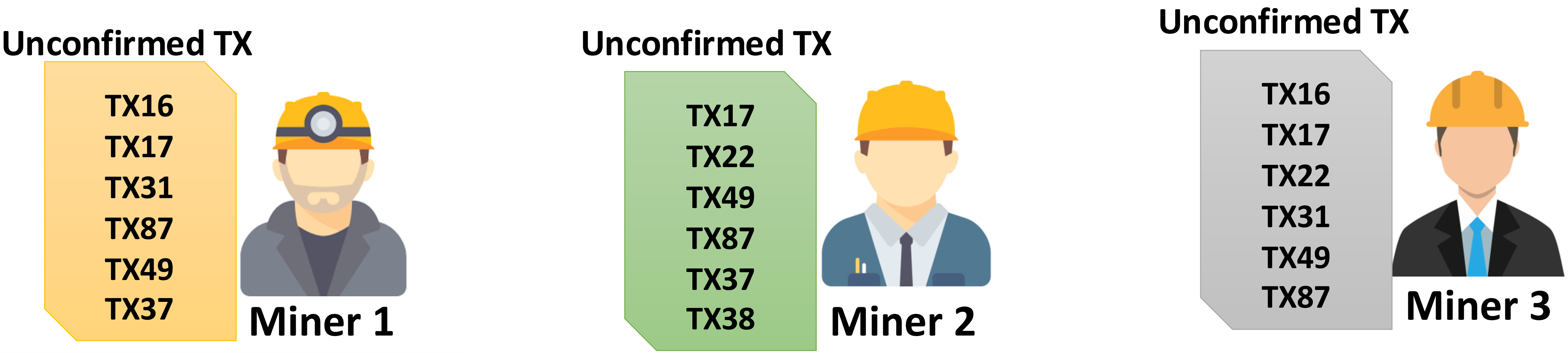

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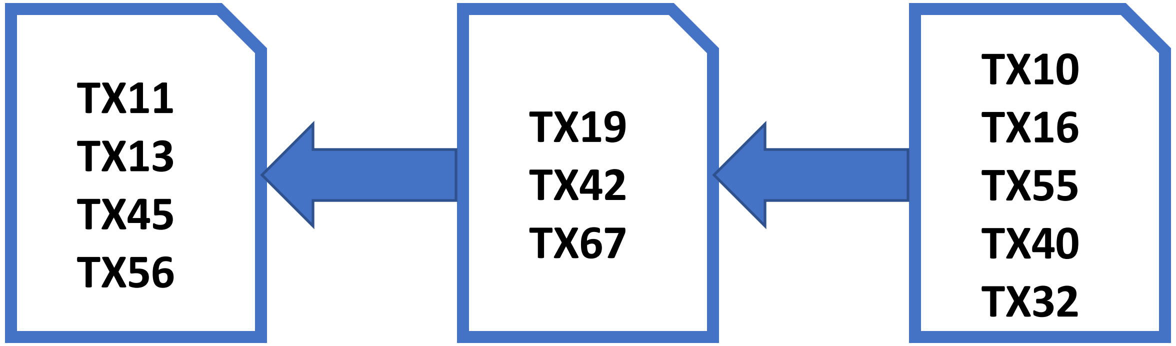

**Liveness:** Add a block as long as it is correct (contains valid transactions from the unconfirmed TX list) and move further

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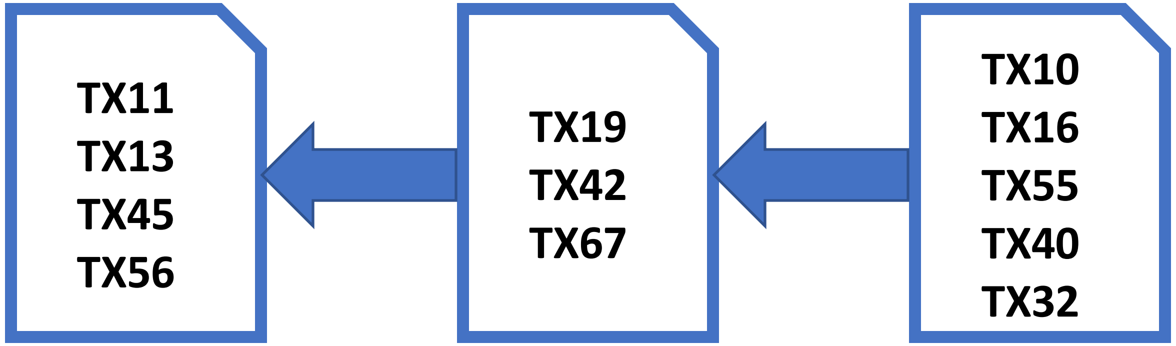

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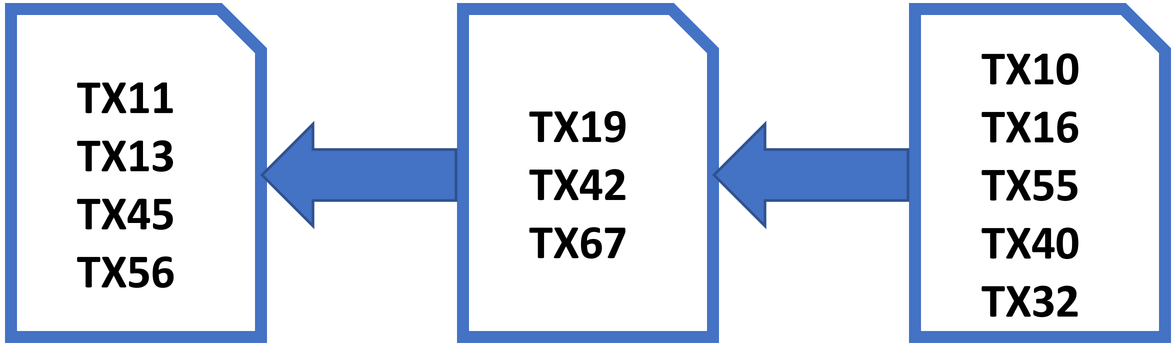

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Will resolve this later!

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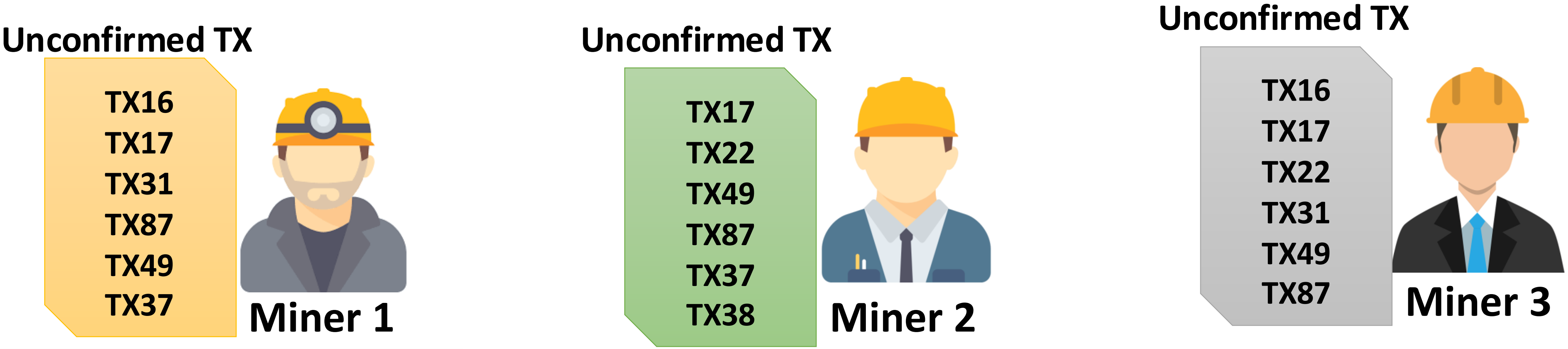

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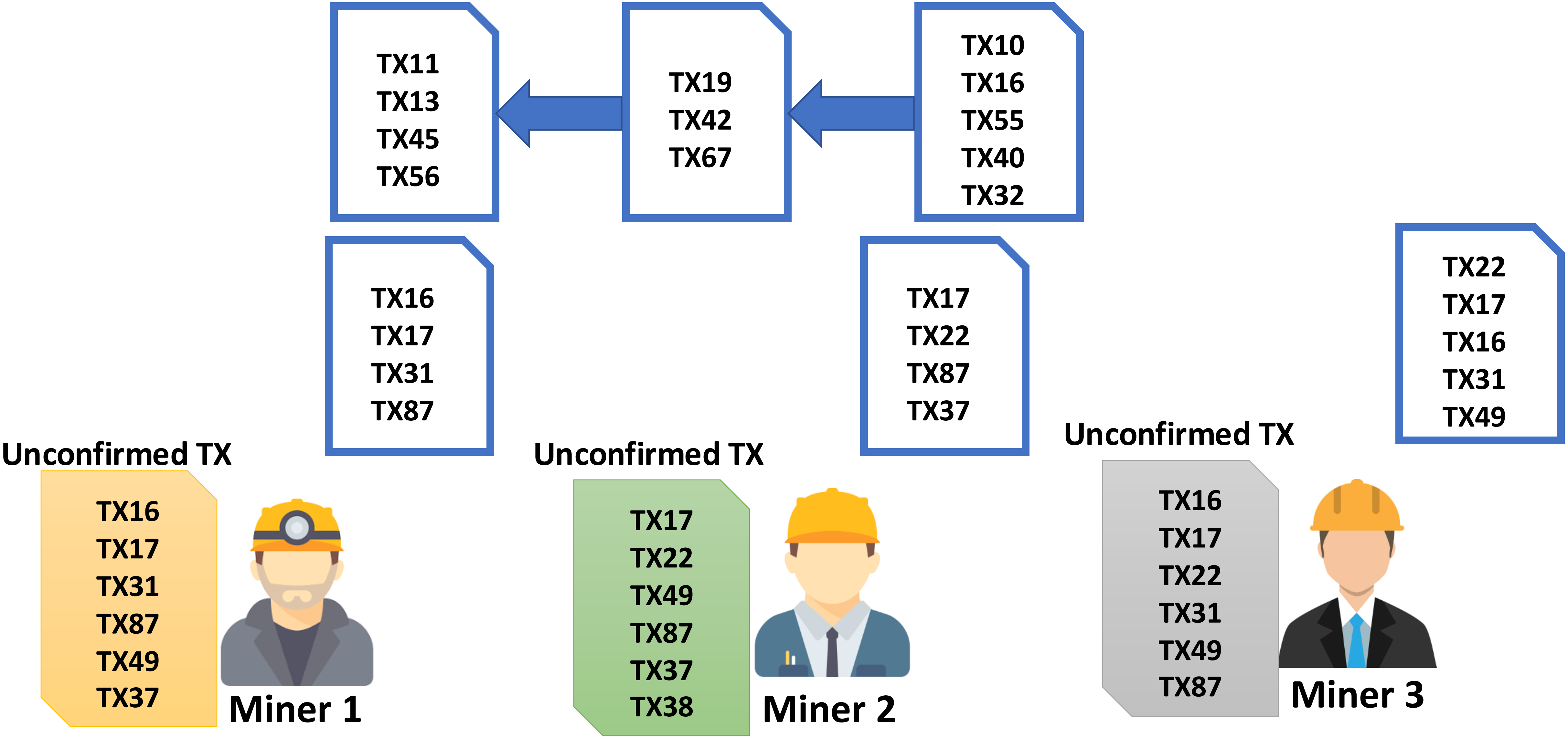
# Nakamoto Consensus (Proof of Work)



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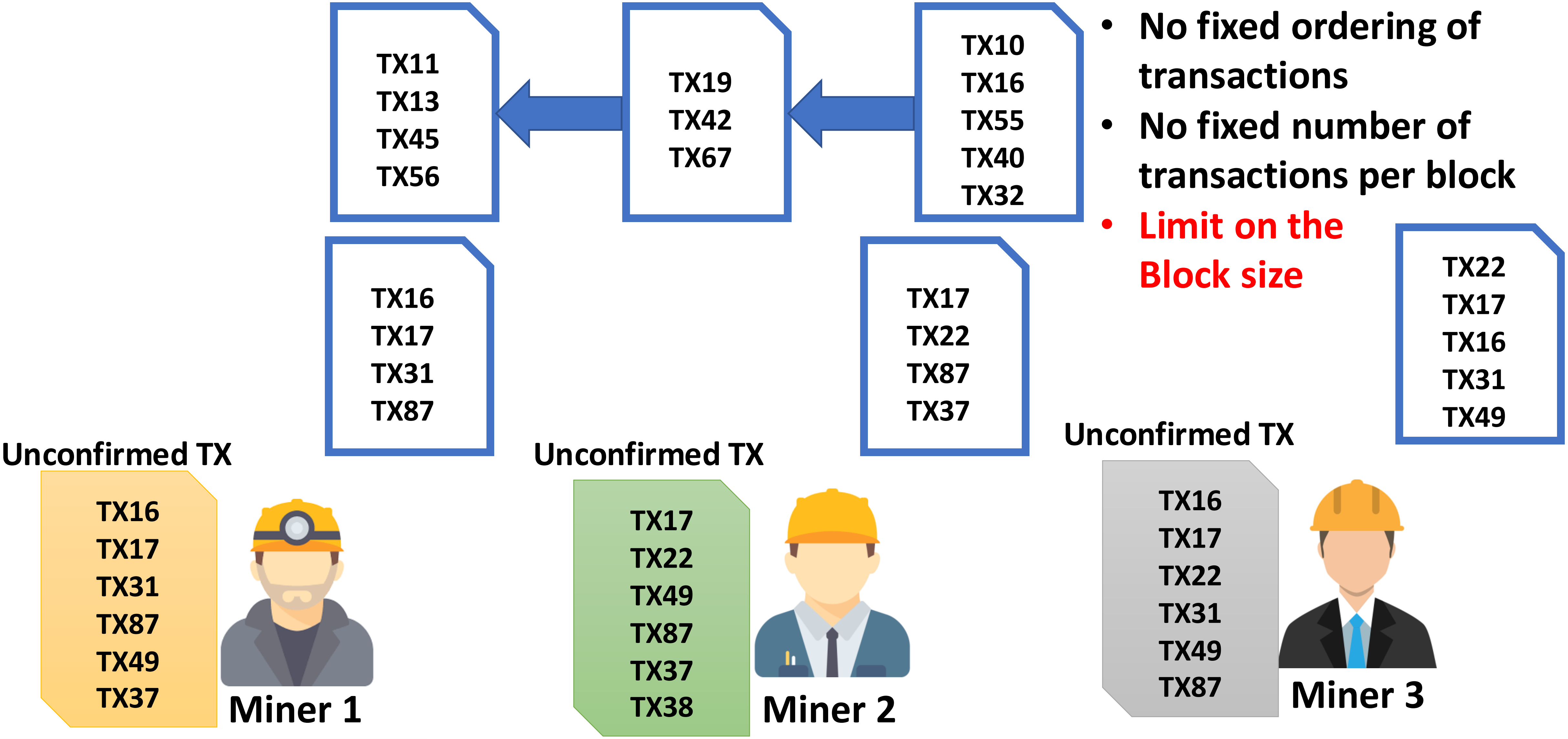
# Nakamoto Consensus (Proof of Work)

- No fixed ordering of transactions
- No fixed number of transactions per block
- Limit on the Block size



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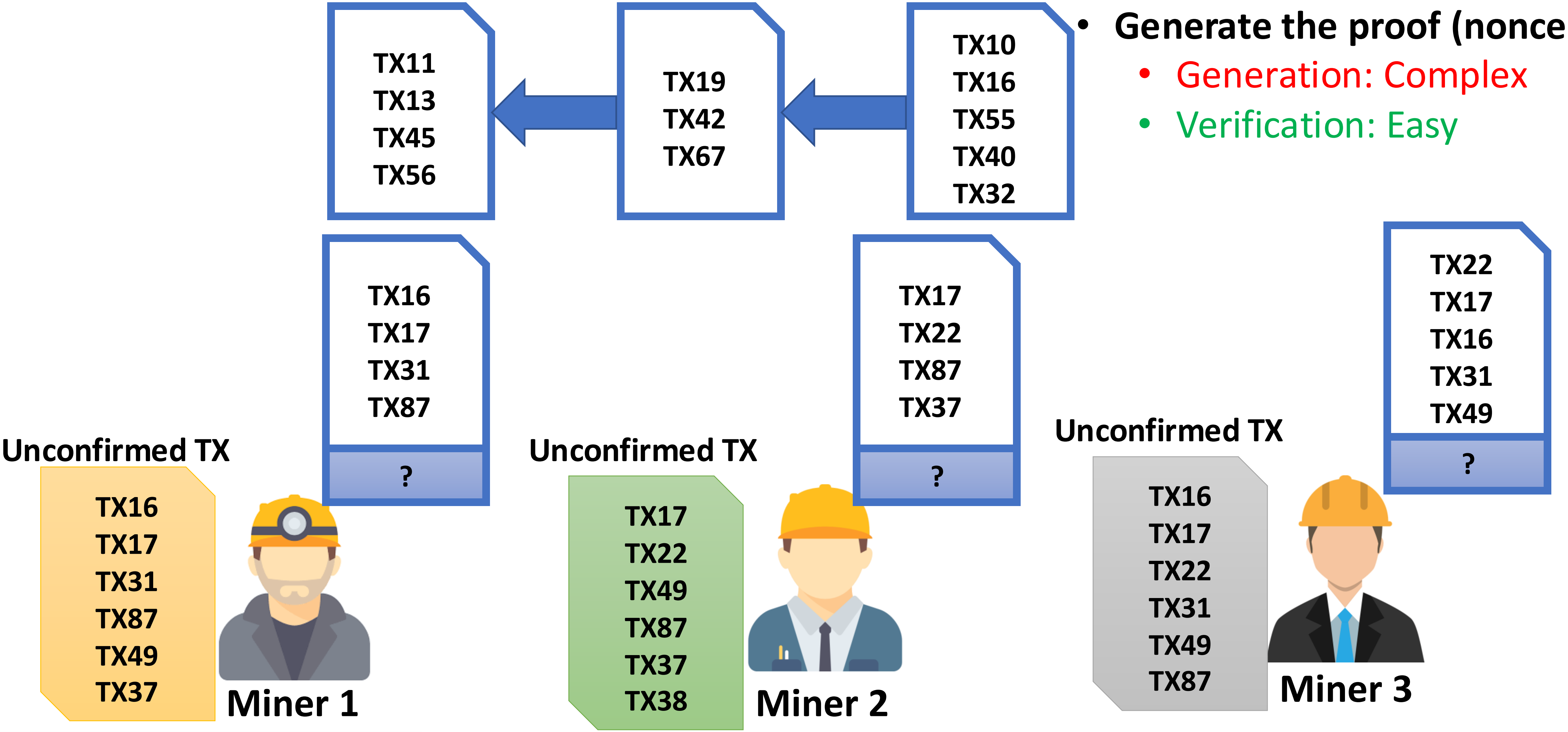
# Nakamoto Consensus (Proof of Work)

- **Generate the proof (nonce)**
  - Generation: Complex
  - Verification: Easy



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**Unconfirmed TX**

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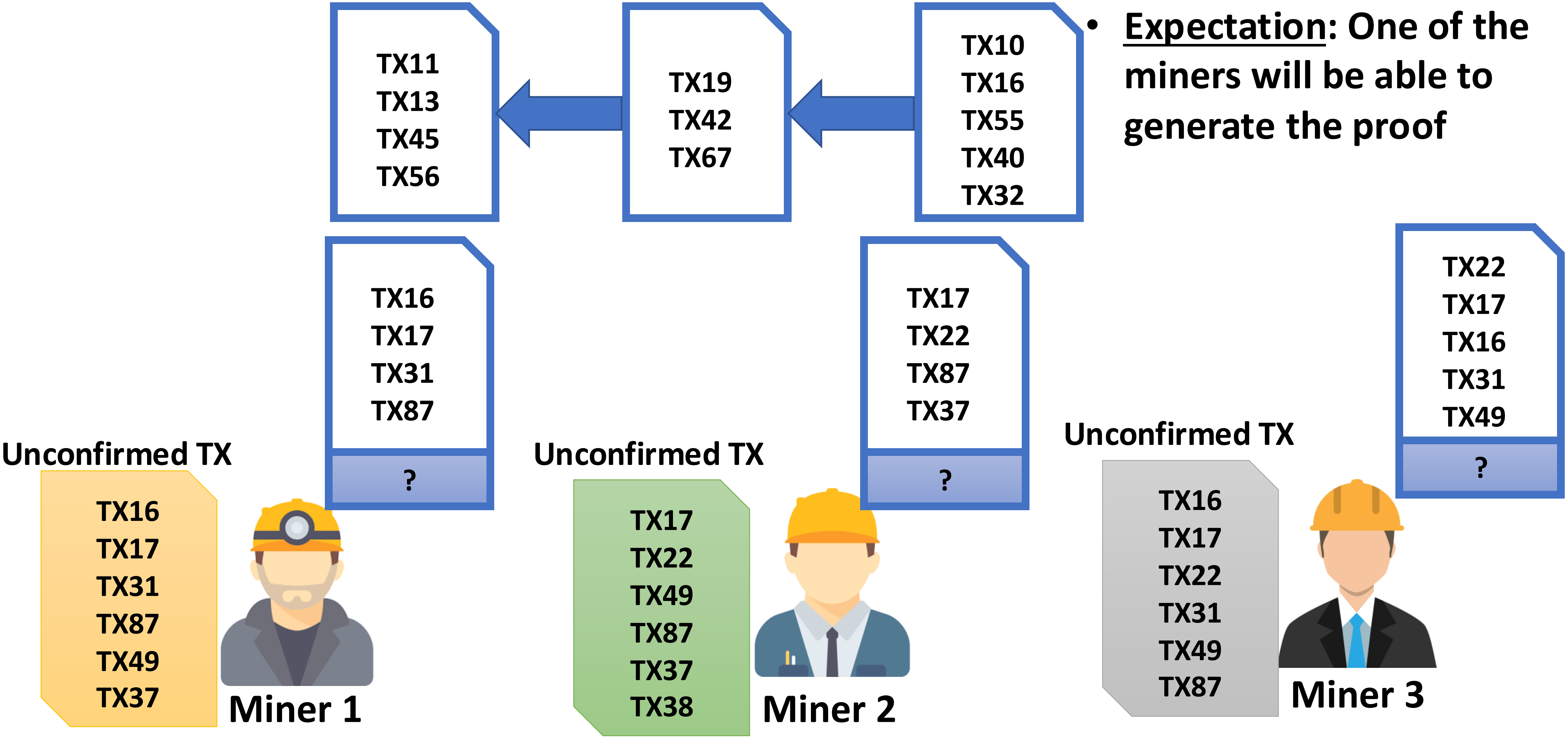
**Miner 3**

# Nakamoto Consensus (Proof of Work)



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- **Expectation**: One of the miners will be able to generate the proof

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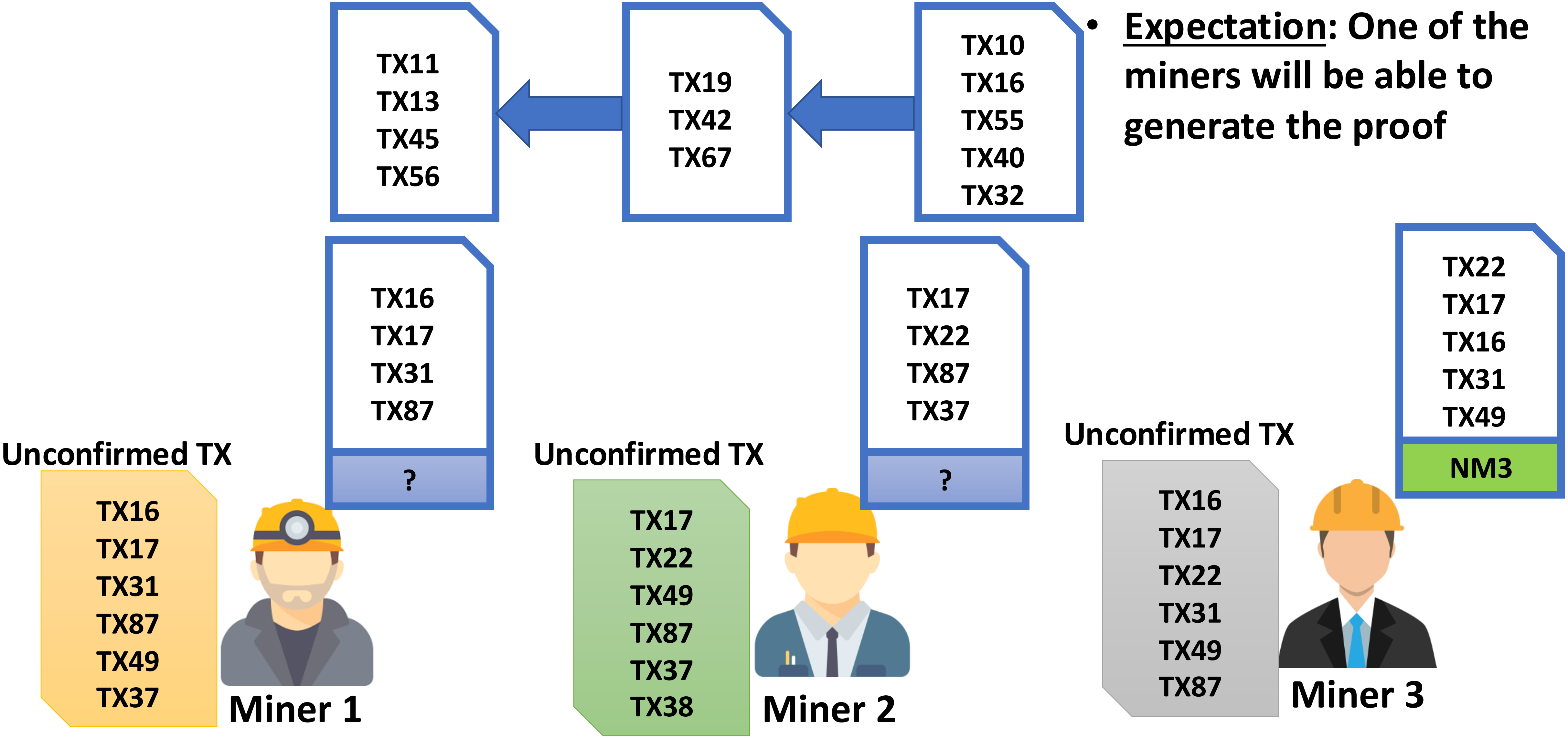

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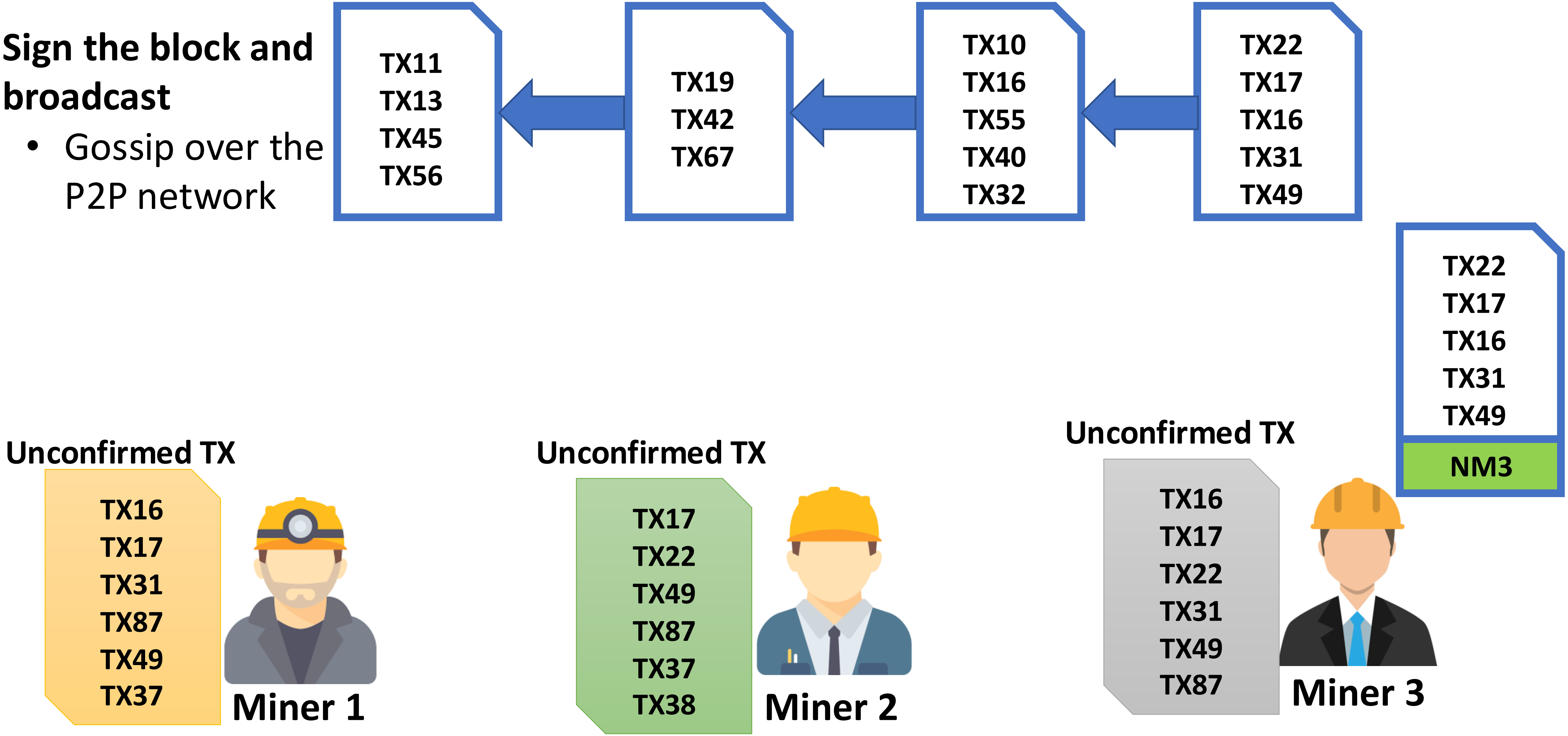
Miner 3

# Nakamoto Consensus (Proof of Work)

- **Sign the block and broadcast**
    - Gossip over the P2P network



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**Unconfirmed TX**

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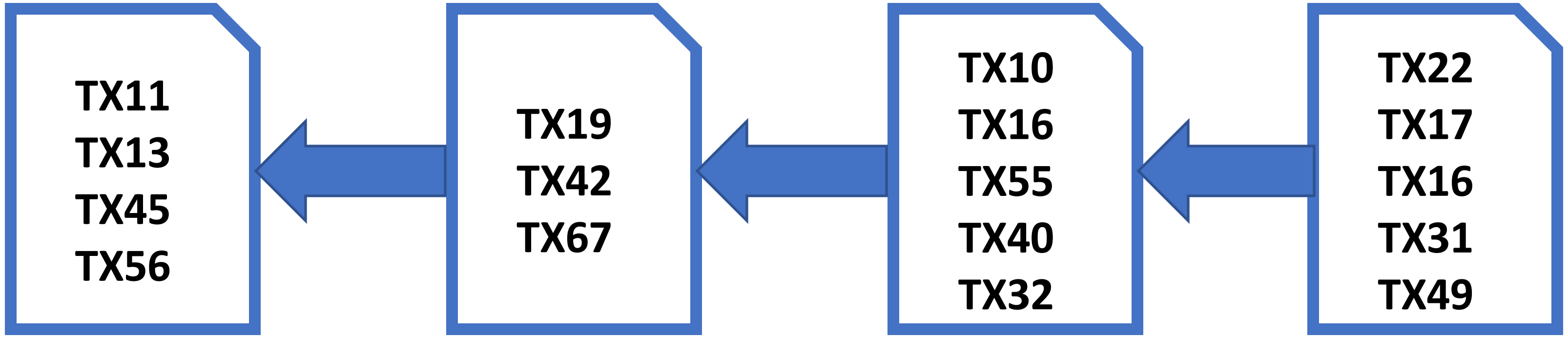
**Miner 3**

# Nakamoto Consensus (Proof of Work)

- Remove the transactions from unconfirmed TX list



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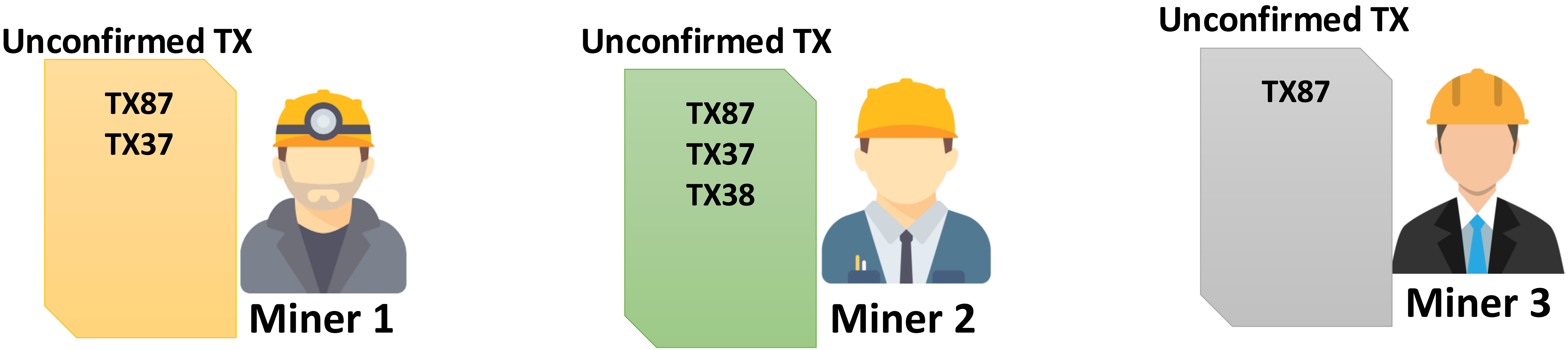

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Unconfirmed TX

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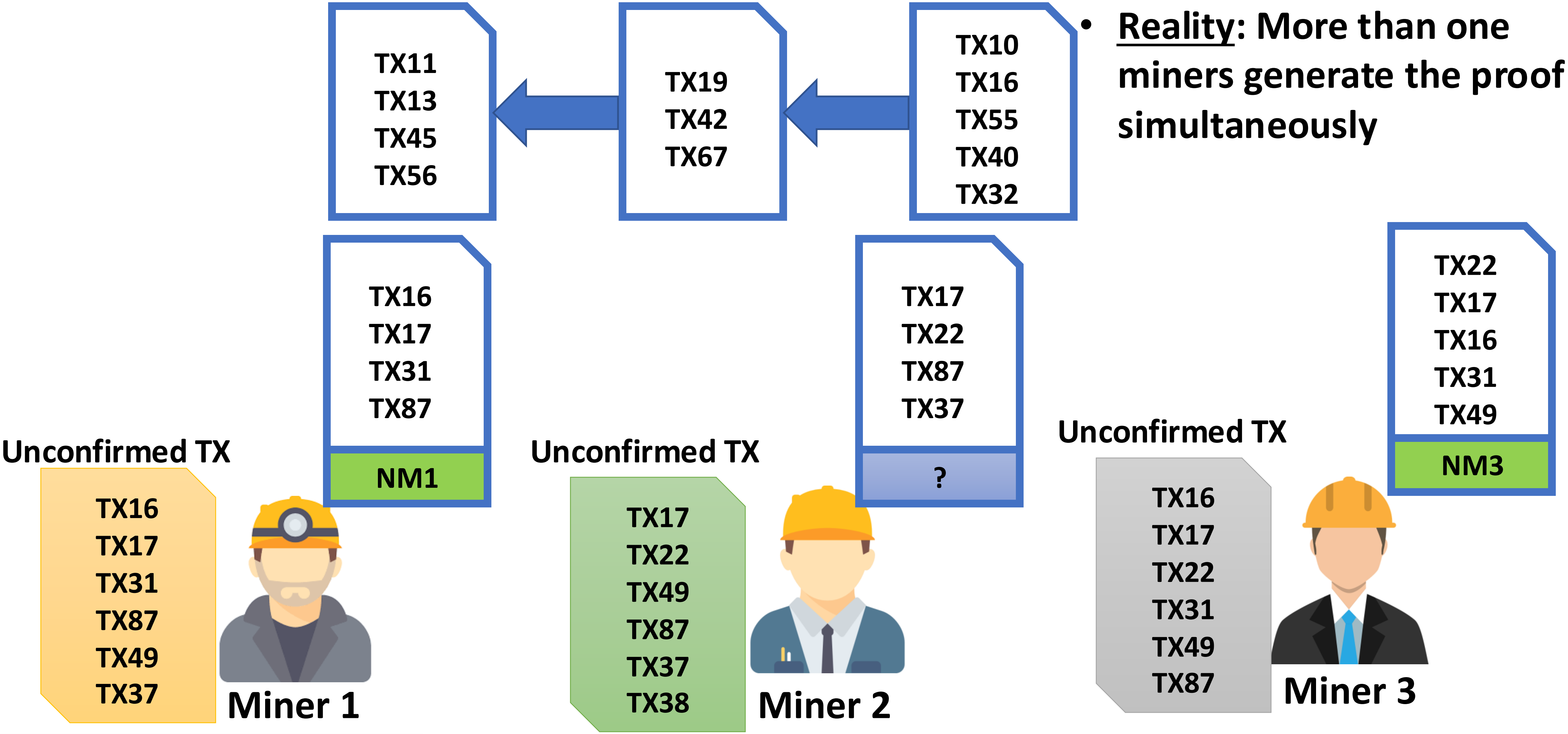
# Nakamoto Consensus (Proof of Work)

- **Reality**: More than one miners generate the proof simultaneously



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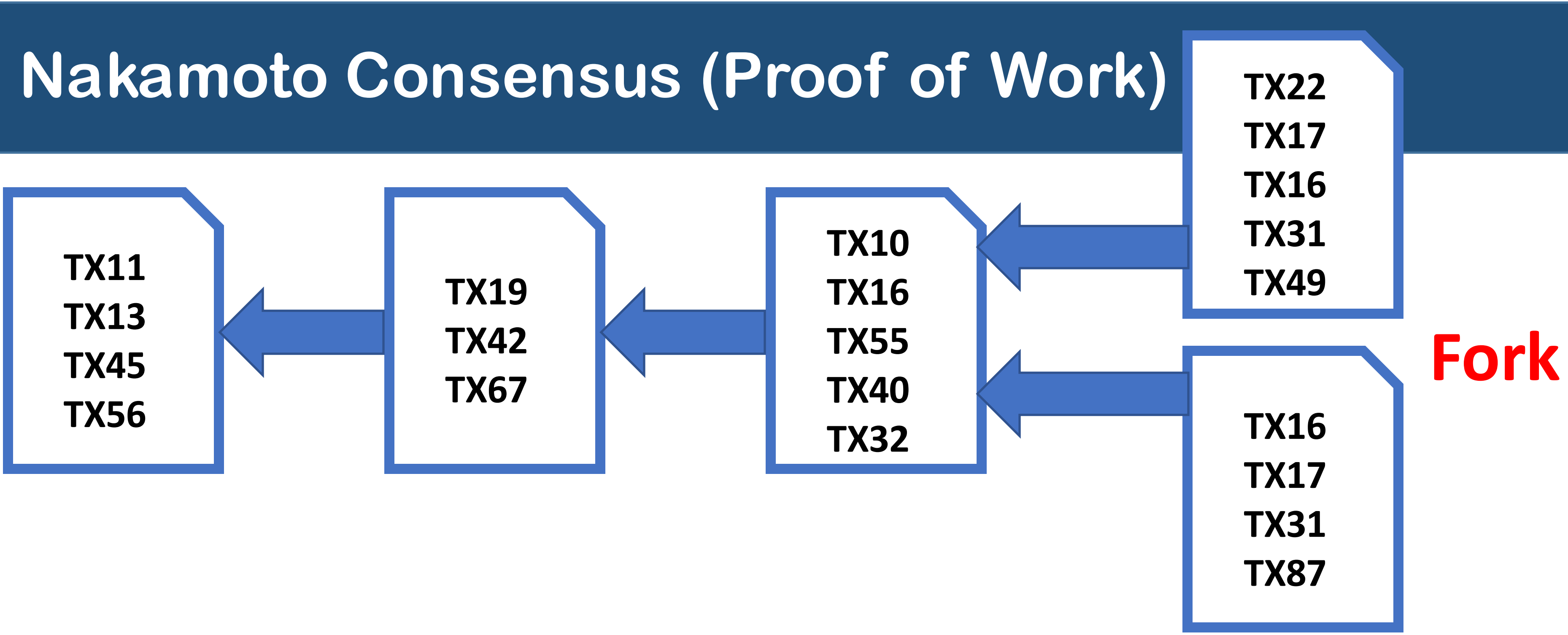

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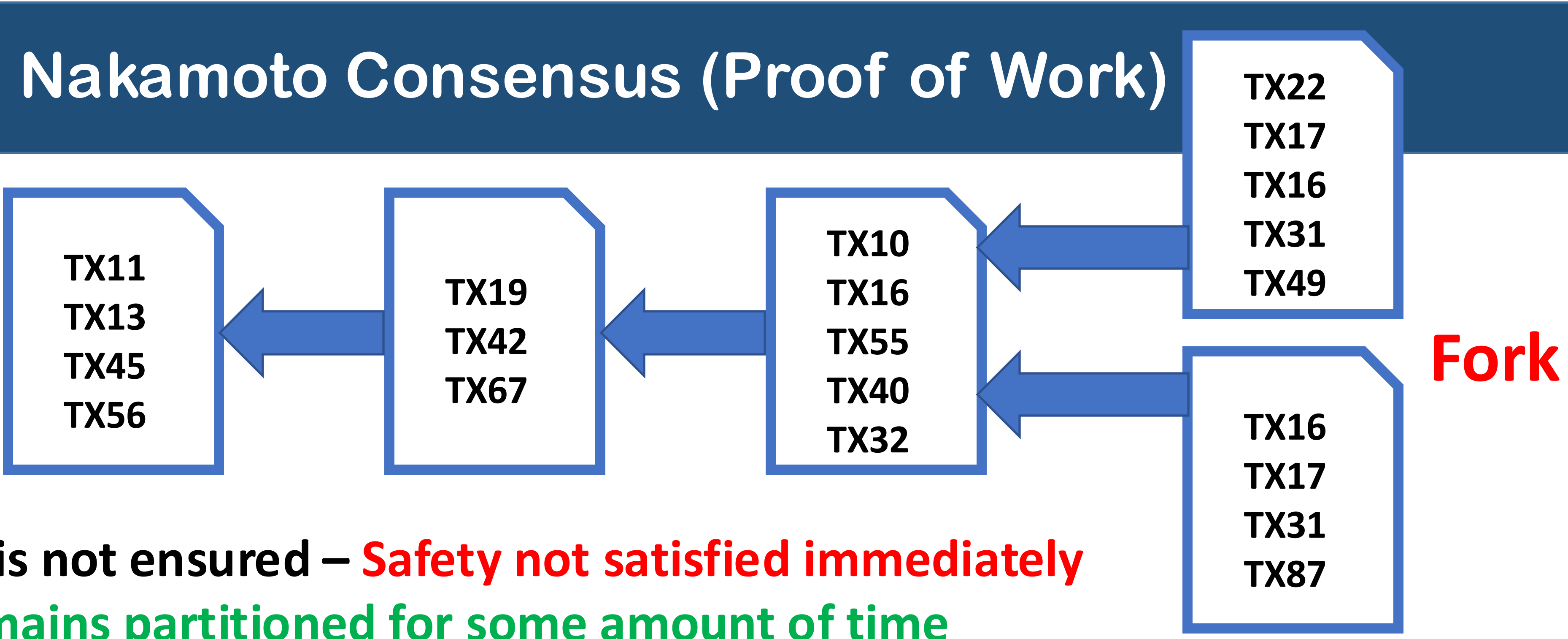

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Fork

**Consensus finality is not ensured – Safety not satisfied immediately**

- **The network remains partitioned for some amount of time**

**Unconfirmed TX**

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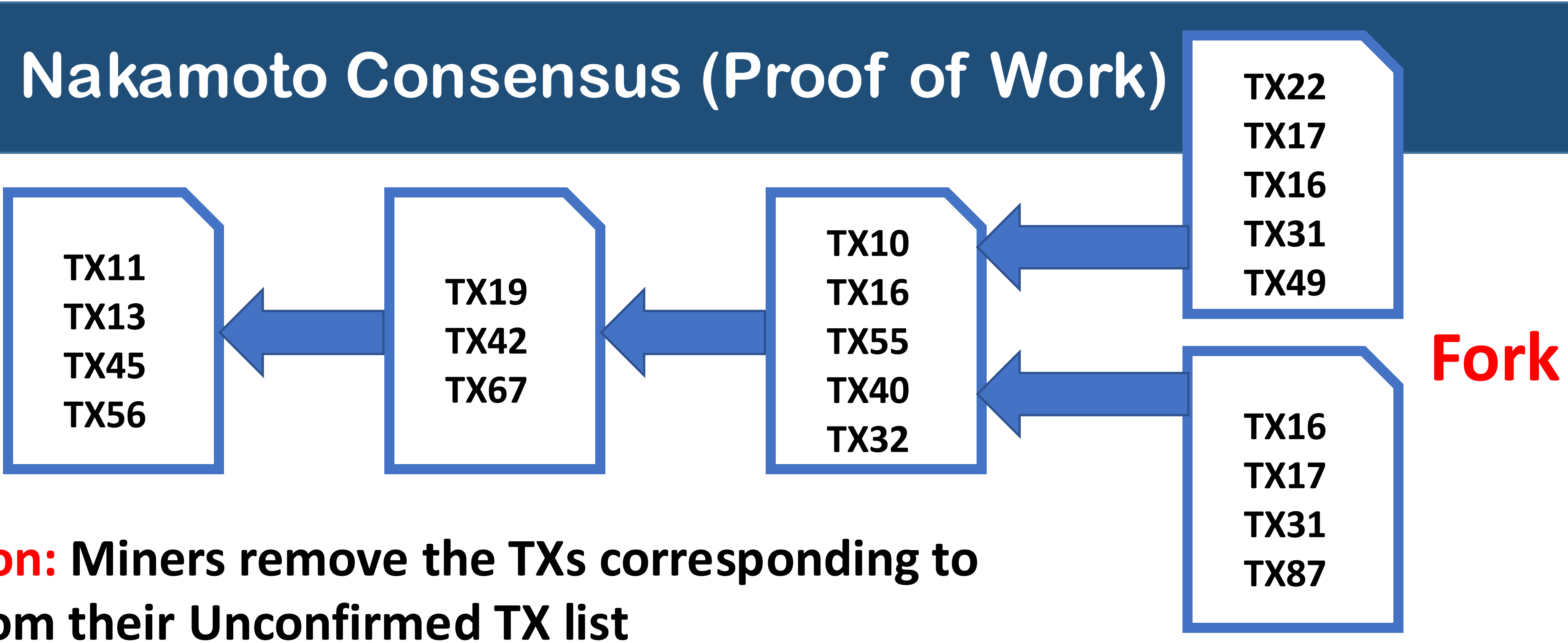
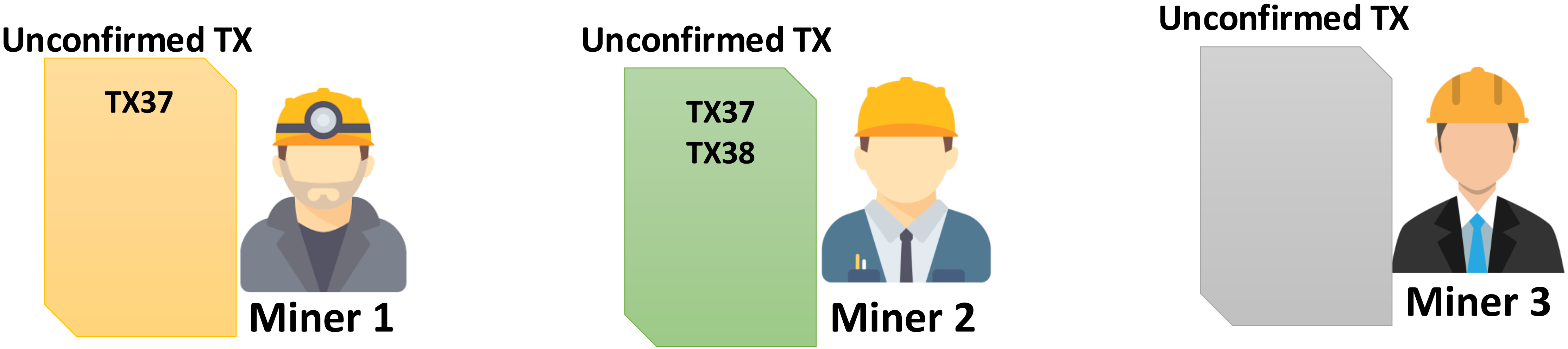


**Momentary Decision:** Miners remove the TXs corresponding to both the blocks, from their Unconfirmed TX list



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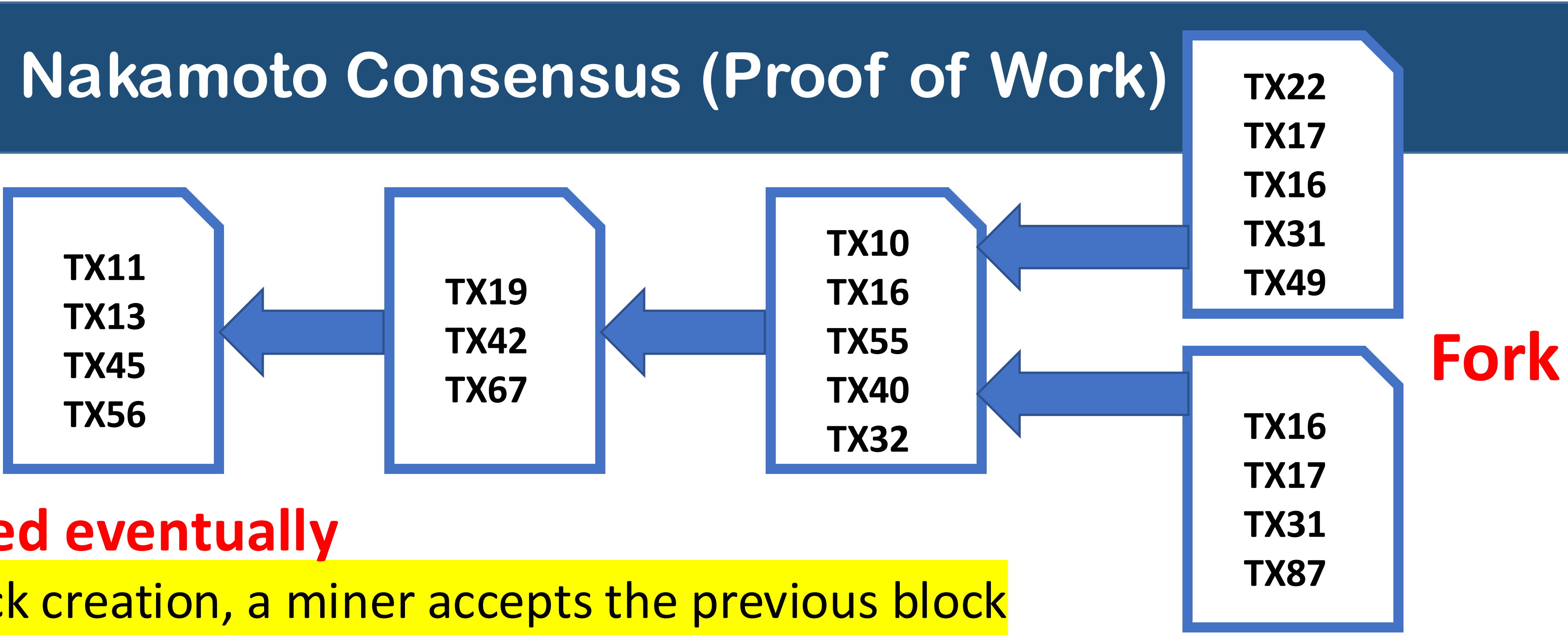
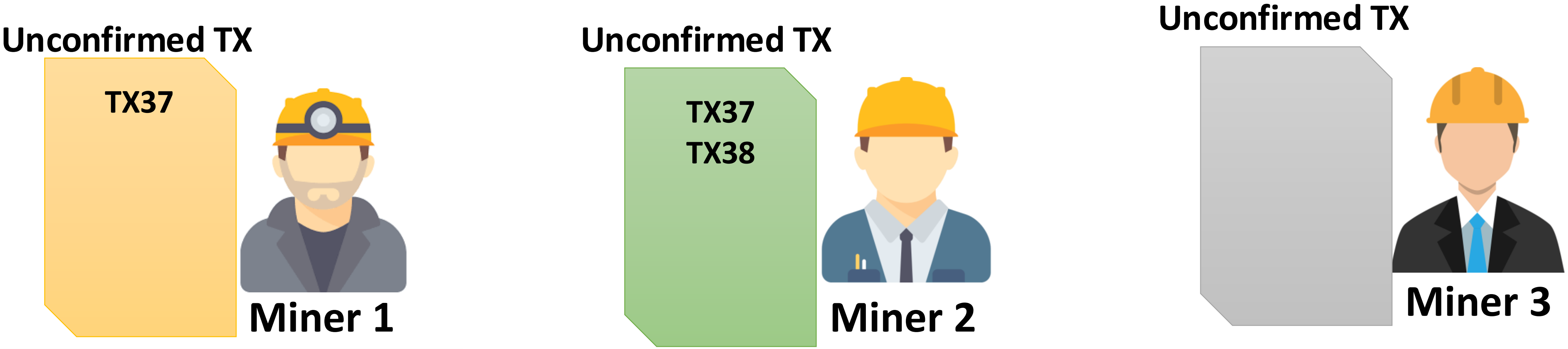


**Forks are resolved eventually**

- For the next block creation, a miner accepts the previous block that it hears from the majority of the neighbor



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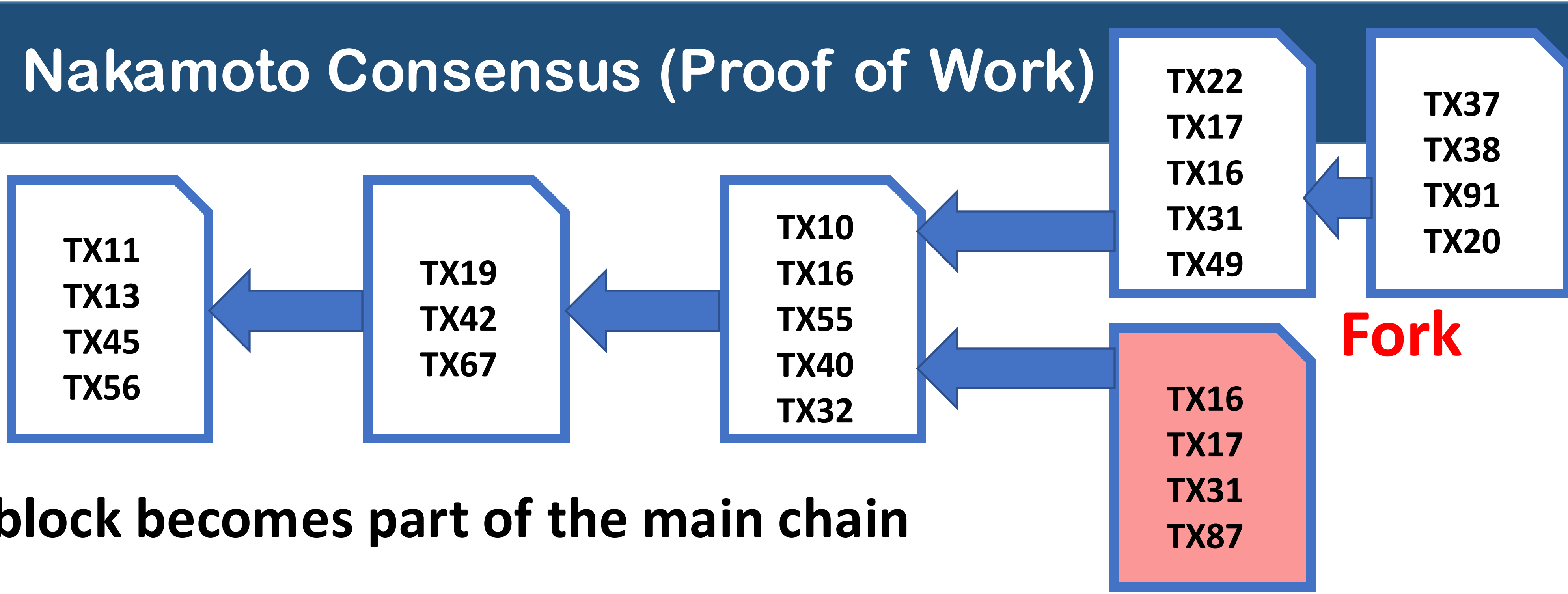

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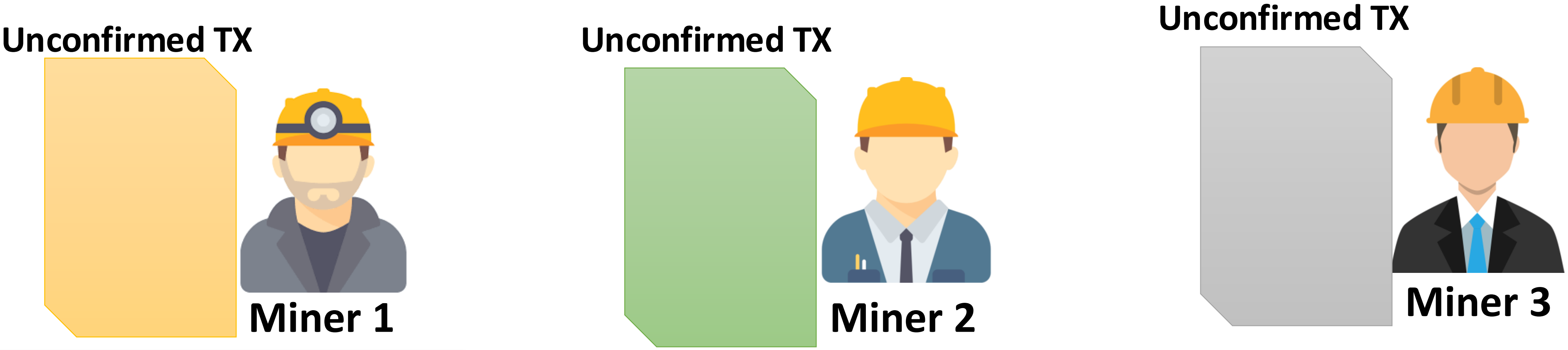
Fork

Eventually, one block becomes part of the main chain



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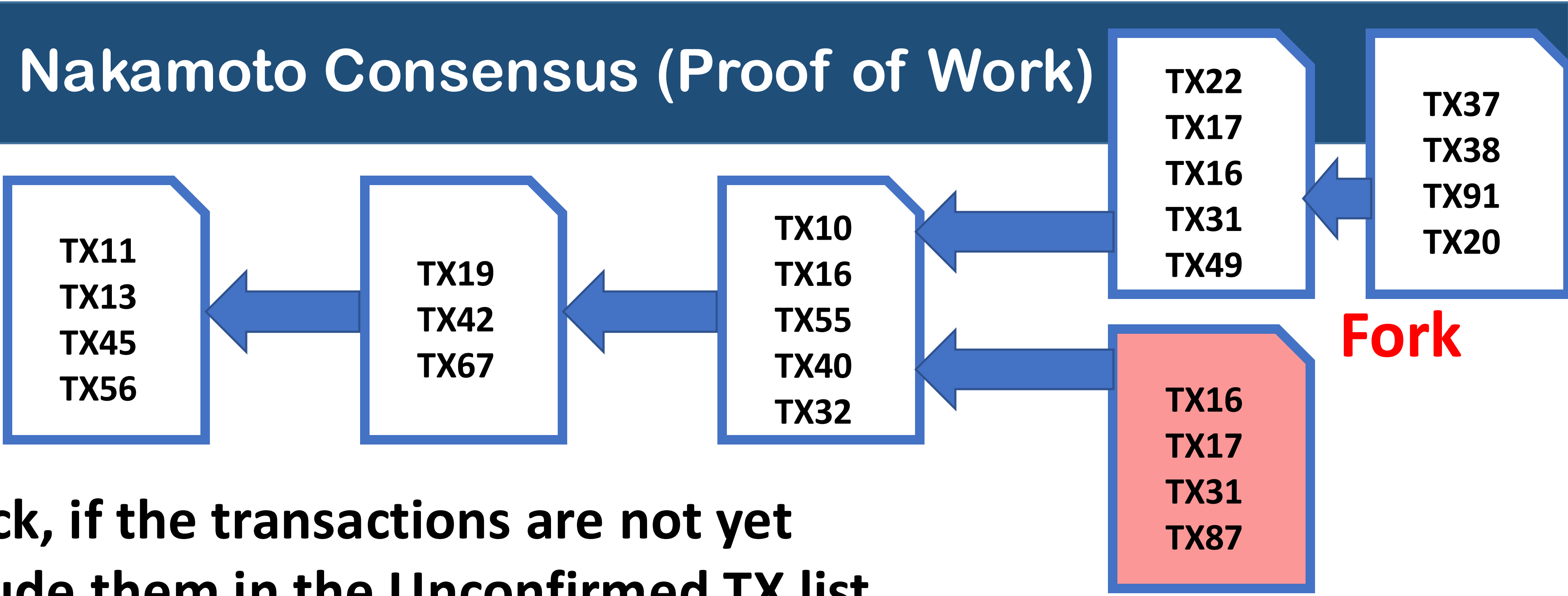
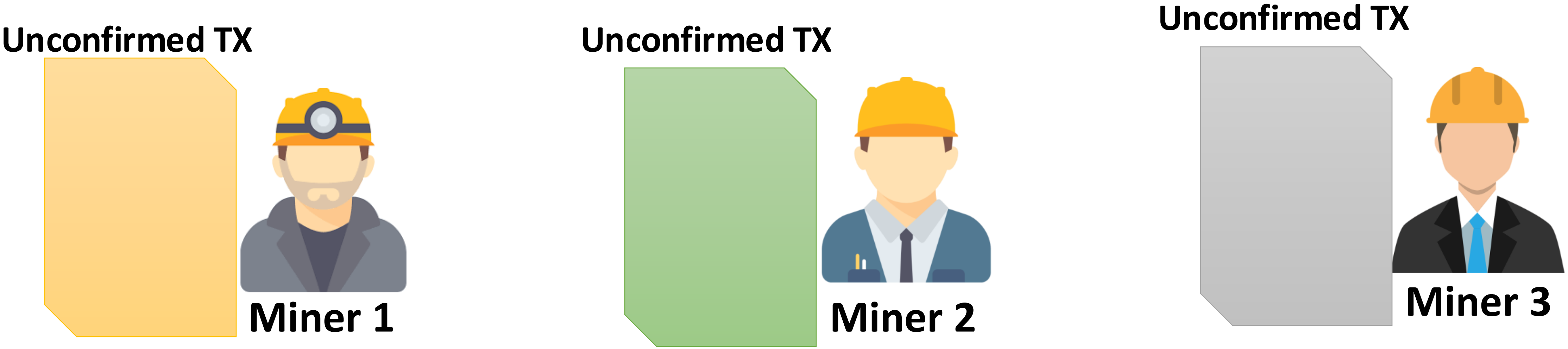


For a forked block, if the transactions are not yet committed, include them in the Unconfirmed TX list



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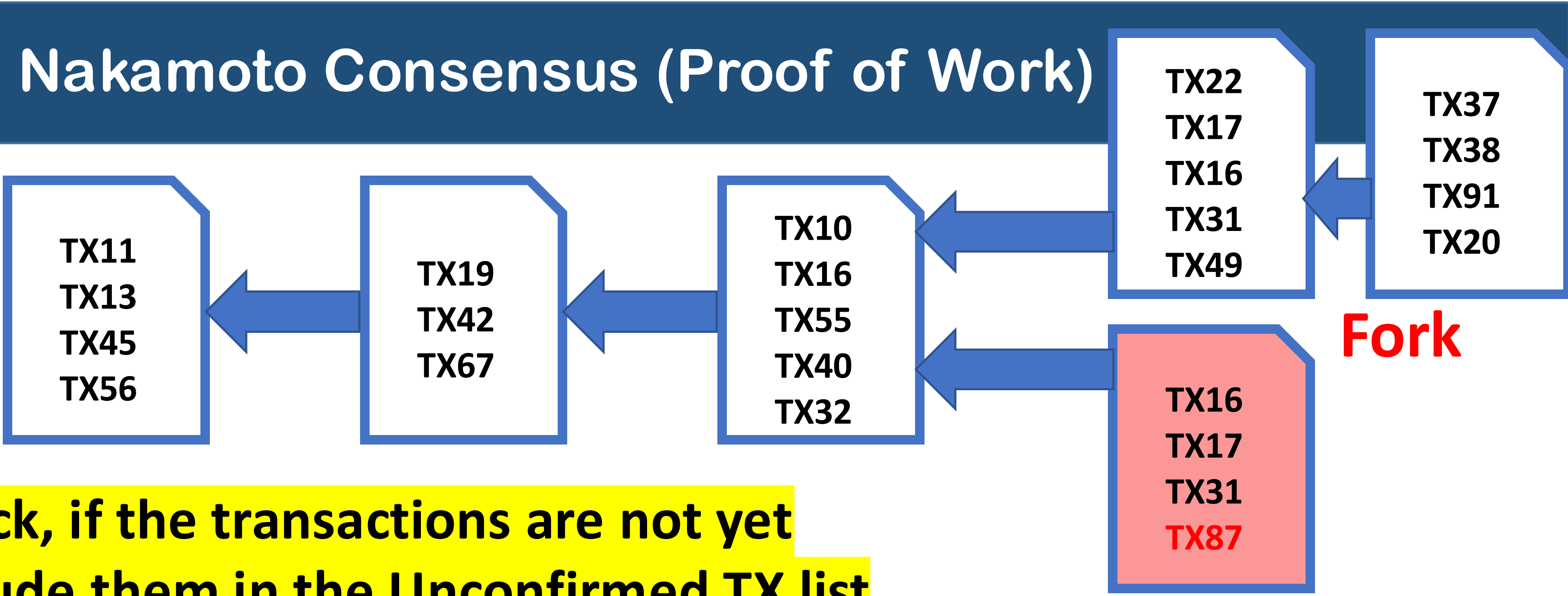

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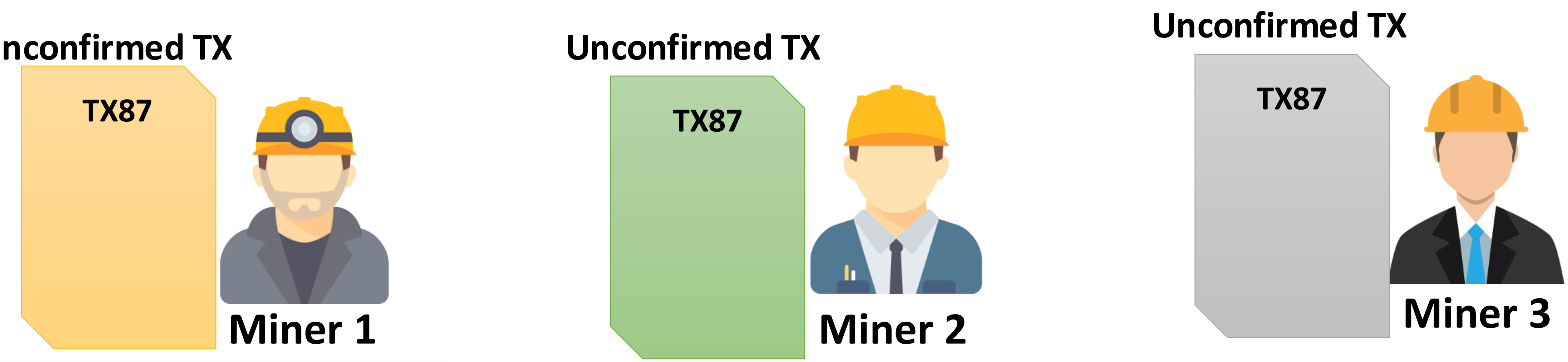

Unconfirmed TX

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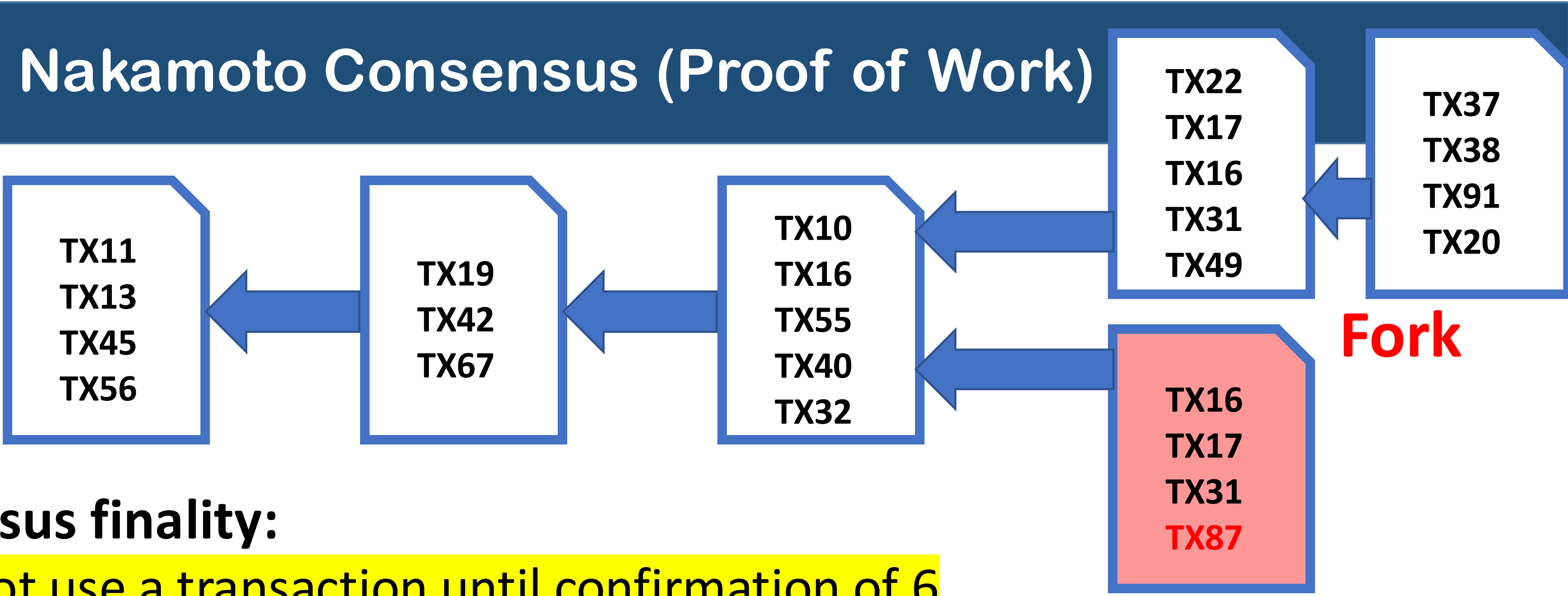
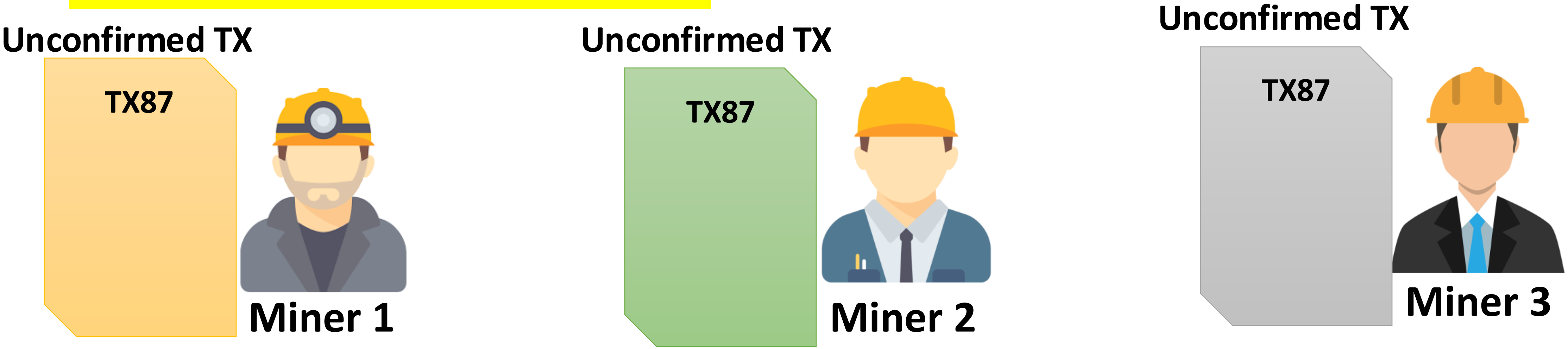
Miner 3

# Nakamoto Consensus (Proof of Work)



**Eventual consensus finality:**

- (Bitcoin) Cannot use a transaction until confirmation of 6 blocks – ensured through scripts



# Security Measures for PoW

- **Sybil Attacks**
  - Attacker attempts to fill the network with the clients under its control
  - Create multiple identities (multiple public key addresses) to control the network – refuse to relay valid blocks or relay attacked blocks
  - **Solution:** Diversify the connections – Bitcoin allows one outbound connection to per /16 block of IP addresses – cannot make both 202.141.81.2/16 and 202.141.80.18/16 as the peers

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- **Denial of Service (DoS)**
  - Send a lot of data to a node – block the processing power
  - **Solution:** Limit forwarding of blocks, disconnect a peer that sends too many transactions

# Breaking PoW

- Bitcoin PoW is **computationally difficult** to break, but not **impossible**

- Attackers can deploy high power servers to do more work than the total work of the blockchain

- A known case of successful double-spending
  - (November 2013) “it was discovered that the GHash.io mining pool appeared to be engaging in repeated payment fraud against *BetCoin Dice*, a gambling site” [Source: https://en.bitcoin.it/]

# The Monopoly Problem

- PoW depends on the computing resources available to a miner
  - Miners having more resources have more probability to complete the work

- Monopoly can increase over time (*Tragedy of the Commons*)
  - Miners will get less reward over time
  - Users will get discouraged to join as the miner
  - Few miners with large computing resources may get control over the network

- **51% Attack:** A group of miners control more than 50% of the hash rate of the network
  - Hypothetical as of now for Bitcoin (as the network is large), but not impossible (happened for Kryptom – Ethereum based blockchain, in August, 2016)

# The Limit of PoW

- **The Good:** A fully decentralized consensus for permissionless models
  - works good for cryptocurrencies – serves its purposes

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  - works good for cryptocurrencies – serves its purposes
- **The Bad:** Do not trust the individuals, but trust the society as a whole
  - You need a real large network to prevent the 51% attack – **not at all suitable for enterprise applications**
- **The Ugly**: Low transaction throughput, Overuse of computing power !!
  - (Bitcoin) 3.3 to 7 transactions per second, (Ethereum) ~15 transactions per second
  - Millions of miners – thousands tries, but only one gets the success

# Bitcoin Energy Consumption

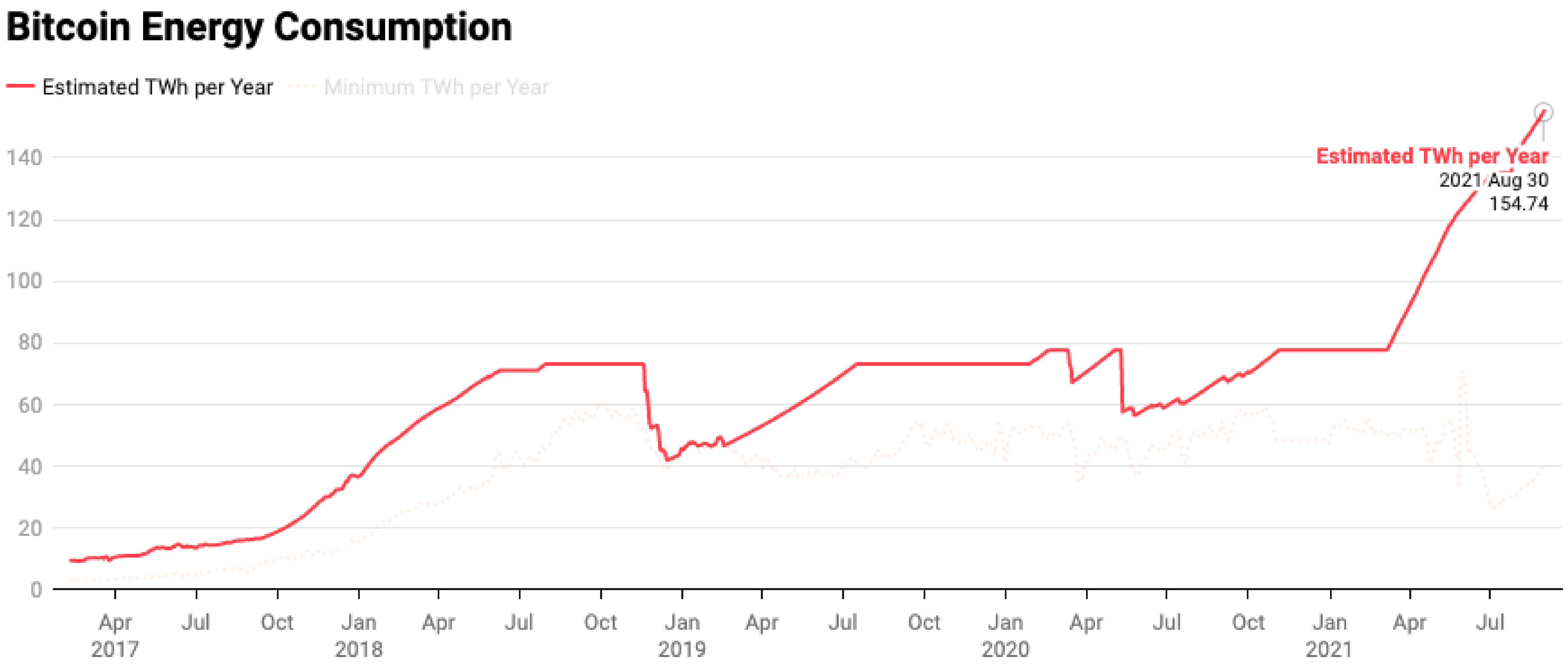
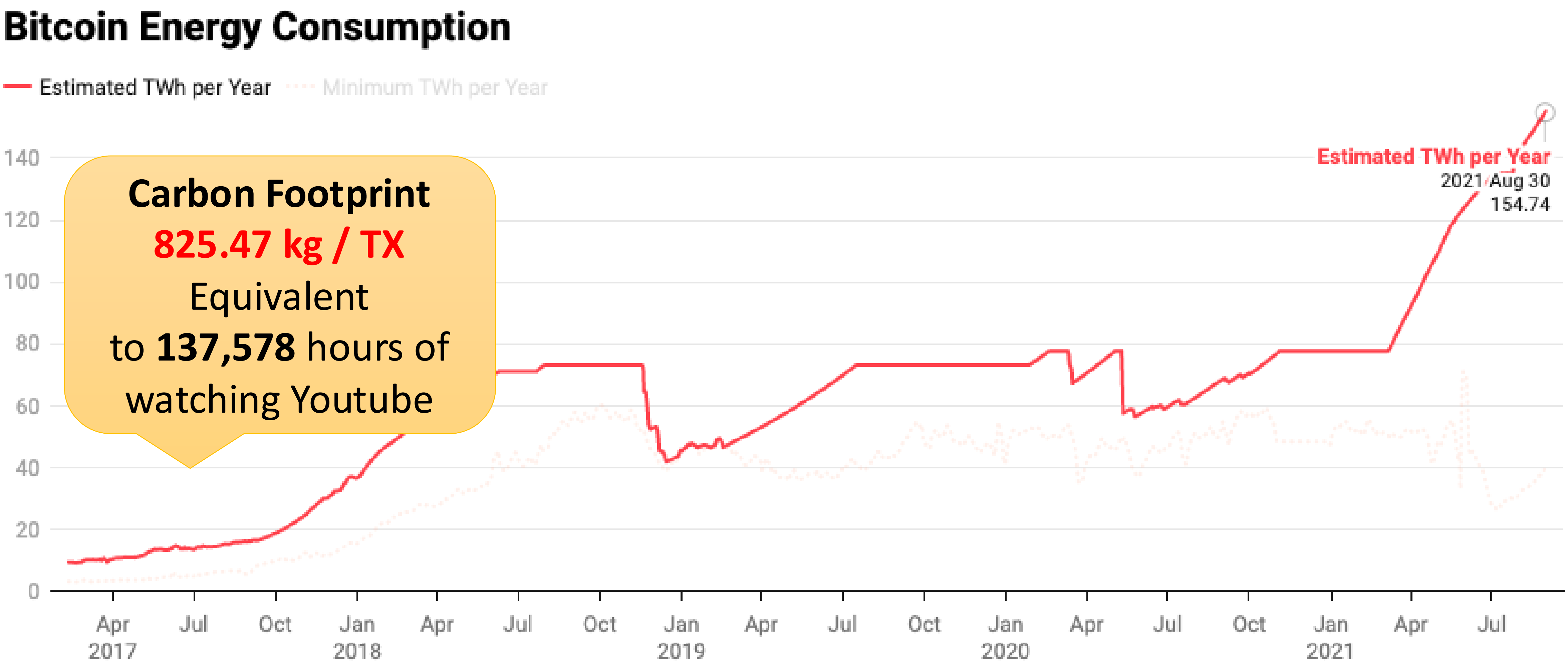


**Image Source: Digiconomist Bitcoin Energy Consumption Index**

# Bitcoin Energy Consumption



**Carbon Footprint**

**825.47 kg / TX**

Equivalent

to **137,578** hours of

watching Youtube

**Image Source: Digiconomist Bitcoin Energy Consumption Index**

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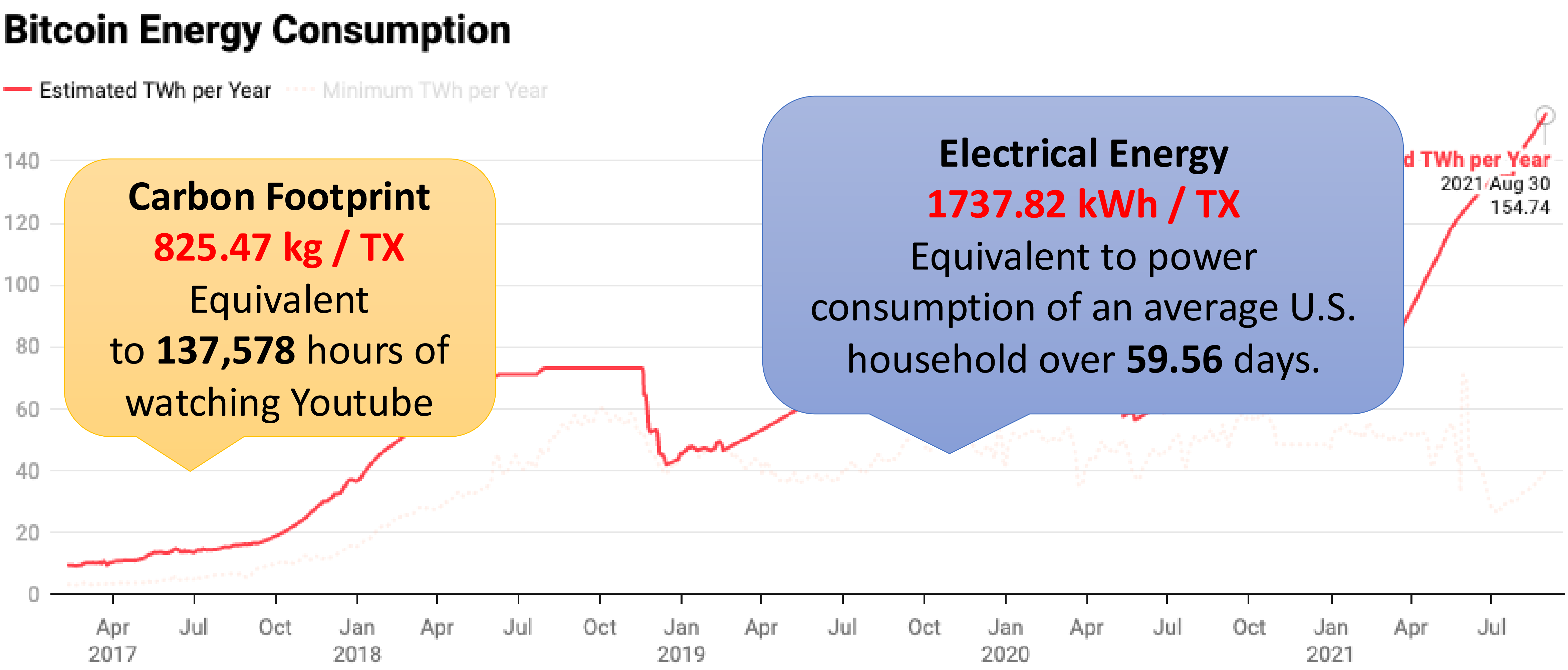

**Carbon Footprint**

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**Electrical Energy**

**1737.82 kWh / TX**

Equivalent to power consumption of an average U.S. household over **59.56** days.

**Image Source: Digiconomist Bitcoin Energy Consumption Index**

# Proof of Stake (PoS)

- Possibly proposed in 2011 by a Member in Bitcoin Forum - https://bitcointalk.org/index.php?topic=27787.0
  - Make a transition from PoW to PoS when bitcoins are widely distributed

- PoW vs PoS
  - **PoW**: Probability of mining a block depends on the work done by the miner
  - **PoS**: Amount of bitcoin that the miner holds – Miner holding 1% of the Bitcoin can mine 1% of the PoS blocks.

# Proof of Stake (PoS)

- Provides increased protection
  - Executing an attack is expensive, you need more Bitcoins
  - **Reduced incentive for attack** – the attacker needs to own a majority of bitcoins – an attack will have more affect on the attacker

- Variants of “stake”
  - Randomization in combination of the stake (*used in Nxt and BlackCoin*)
  - **Coin-age**: Number of coins multiplied by the number of days the coins have been held (*used in Peercoin*)

# Ethereum PoS

- The default consensus mechanism in Ethereum is PoS
  - Switched to PoS from PoW in 2022
- **Validators:** The users who responsible for checking that new blocks propagated over the network are valid
  - Occasionally creates and propagates new blocks themselves.
- **Ethereum PoS: P**rove that validators have put something of value into the network that can be destroyed if they act dishonestly.
  - Validators explicitly stake capital in the form of ETH into a smart contract on Ethereum
  - If they try to defraud the network (*for example by proposing multiple blocks when they ought to send one or sending conflicting attestations*), some or all of their staked ETH can be destroyed.

# Ethereum PoS: Validators

- To participate as a validator, a user must
  - Deposit 32 ETH into the deposit contract
  - Run three separate pieces of software: an execution client, a consensus client, and a validator.

- On depositing their ETH, the user joins an activation queue that limits the rate of new validators joining the network.
  - Once activated, validators receive new blocks from peers on the Ethereum network.

- The transactions delivered in the block are re-executed to check that the proposed changes to Ethereum's state are valid, and the block signature is checked.
  - The validator then sends a vote (called an attestation) in favor of that block across the network.

# Ethereum PoS: Validators

- Time is divided into slots (12 seconds) and epochs (32 slots).
    - One validator is randomly selected (selected pseudo-randomly using RANDAO -- https://www.randao.org/) to be a block proposer in every slot.
    - This validator is responsible for creating a new block and sending it out to other nodes on the network.
- In every slot, a committee of validators is randomly chosen, whose votes are used to determine the validity of the block being proposed.
    - Committees divide up the validator set so that every active validator attests in every epoch, but not in every slot.

# The Need for Randomness

- Two fundamental questions --
  - How do you decide who is going to be the proposer for a new block?
  - How do you decide the committee members?

- The selection process must be **fair** to all validators

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  - **What can be a possible issue with this solution?** Attackers know whose turn is the next – launch a DoS on that validator, or validators can conspire among their Neighbours

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- **Solution:** Use random numbers to produce block producers in each epoch
  - **But, how do you get on-chain randomness?**

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- Use a **group of validators** to propose their own random number – use a mixing function to generate the final output number
  - `Output → mix (input-1, input-2, input-3, …, input-n)`
  - **Condition:** Use a mixing function that gives equal weight to all the inputs

# The Need for Randomness

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  - $(1111 \oplus 1001) \oplus 0101 \rightarrow 0011$

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# RANDAO

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- **Solution:** Let other participants do not see the inputs until all inputs are revealed → Hide the proposed input through cryptographic hash until all the inputs are revealed (**Cryptographic commitments)**
  - Propose the cryptographic hash of the secret (commit phase)
  - Once everyone makes the hash values public, then reveal the original secret value (Reveal phase)

# RANDAO

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  - Ethereum uses BLS signatures (earlier used hash onions)

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- **One possible issue with RANDAO** -- while they prevent a participant from changing their number, they don't actually force the participant to reveal their number.
  - Solution: Verifiable Delay Function (VDF) -- Feed the RANDAO in a function that delay the output – and use the delayed output (the output is guaranteed to be produced after a delay – you cannot arbitrarily delay to reveal the output)
  - Ethereum does not incorporate such solutions yet, is an interesting research topic

# RANDAO in Ethereum

- Every block contains a field `randao_reveal` which is the RANDAO contribution for the block proposer

- The RANDAO contributions for each block is used to compute the chain's RANDAO till the last block
  - The chain's RANDAO (along with the stake contributions from the validators) is used to select the next block proposer and the committee members to validate that block

- Check this for a detailed description of Ethereum PoS: https://ethereum.org/en/developers/docs/consensus-mechanisms/pos/

# Proof of Burn (PoB)

- Miners should show proof that they have *burned* some coins
  - Sent them to a verifiably un-spendable address
  - Expensive just like PoW, but no external resources are used other than the burned coins

- PoW vs PoB – Real resource vs virtual/digital resource

- PoB works by burning PoW mined cryptocurrencies

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**PoS and PoB**

**Ultimately depends on PoW mined cryptocurrencies**

**You cannot use them to bootstrap a new blockchain**

# Proof of Elapsed Time (PoET)

- Proposed by Intel, as a part of Hyperledger Sawtooth – a blockchain platform for building distributed ledger applications

- **Basic idea:**
  - Each participant in the blockchain network waits a random amount of time
  - The first participant to finish becomes the leader for the new block

- How will one verify that the proposer has **really waited** ?
  - Utilize special CPU instruction set – *Intel Software Guard Extension* (SGX) – a trusted execution platform
  - The trusted code is private to the rest of the application
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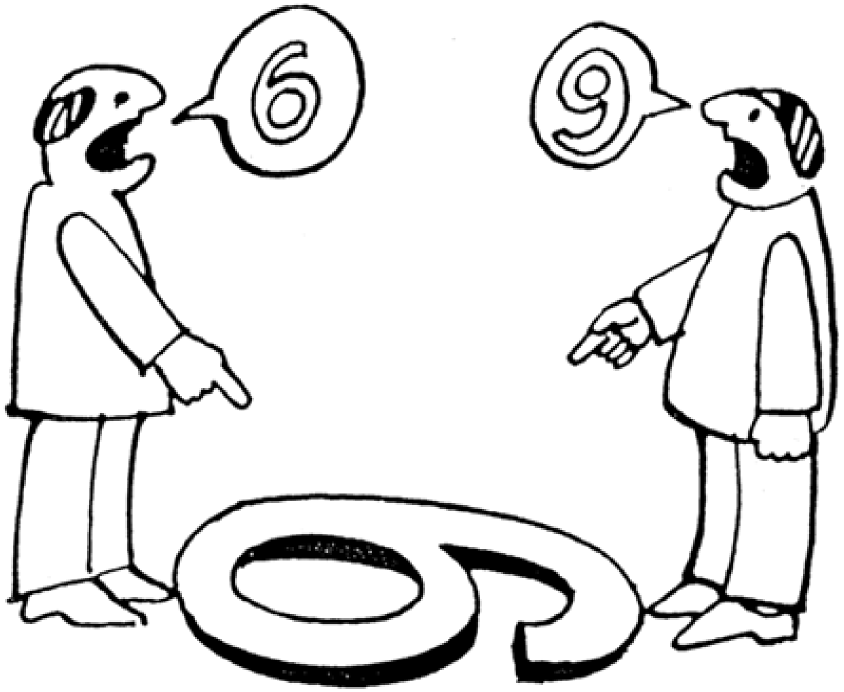
# What Next?

- Enterprise blockchains and Consensus thereafter
- Consensus scalability
- A decade of research on Blockchain (Distributed System?) consensus …



thank you!