An overview of proof-of-work and proof-of-stake consensus

Valeria (Lera) Nikolaenko
The 13th BIU Winter School on cryptography

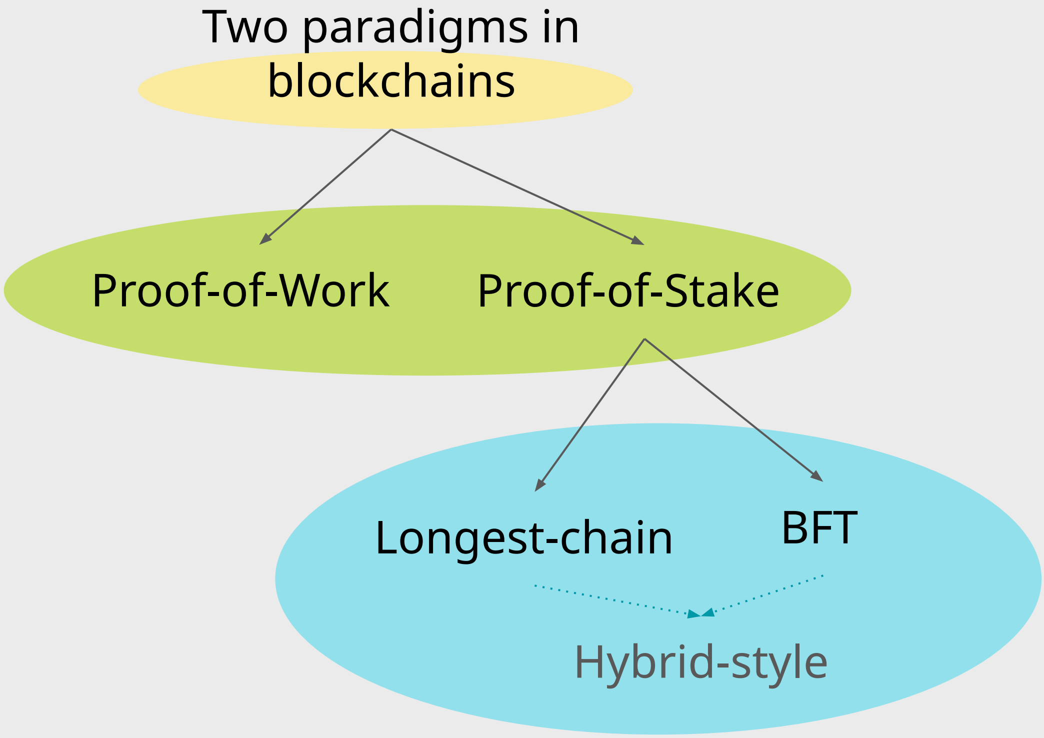
a16z crypto

Outline

0 Def a blockchain

1 PoW vs PoS

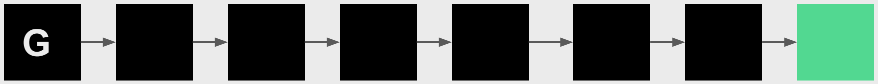
2 Longest-chain vs BFT



0: What is a blockchain?

<u>Block</u>chain : what is it?

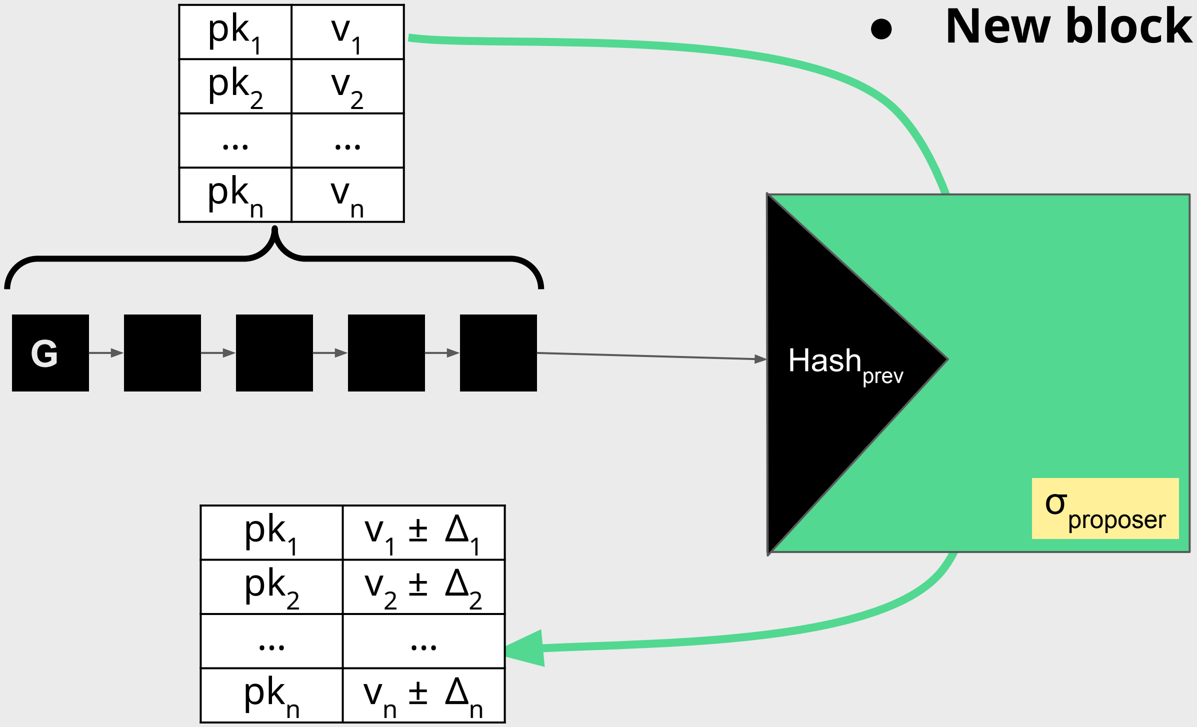
Blockchain is a distributed ledger - a log of transactions*.



- Blockchain is a chain of blocks.
- Each block is a list of transactions + hash of the previous block.
- <u>Safety</u>: everybody agrees on history.
- <u>Liveness</u>: every valid transaction eventually gets added
  => not censoring

Blockchain : what is it?

- **Blockchain's prefix defines a state**
- **New block transforms the state**



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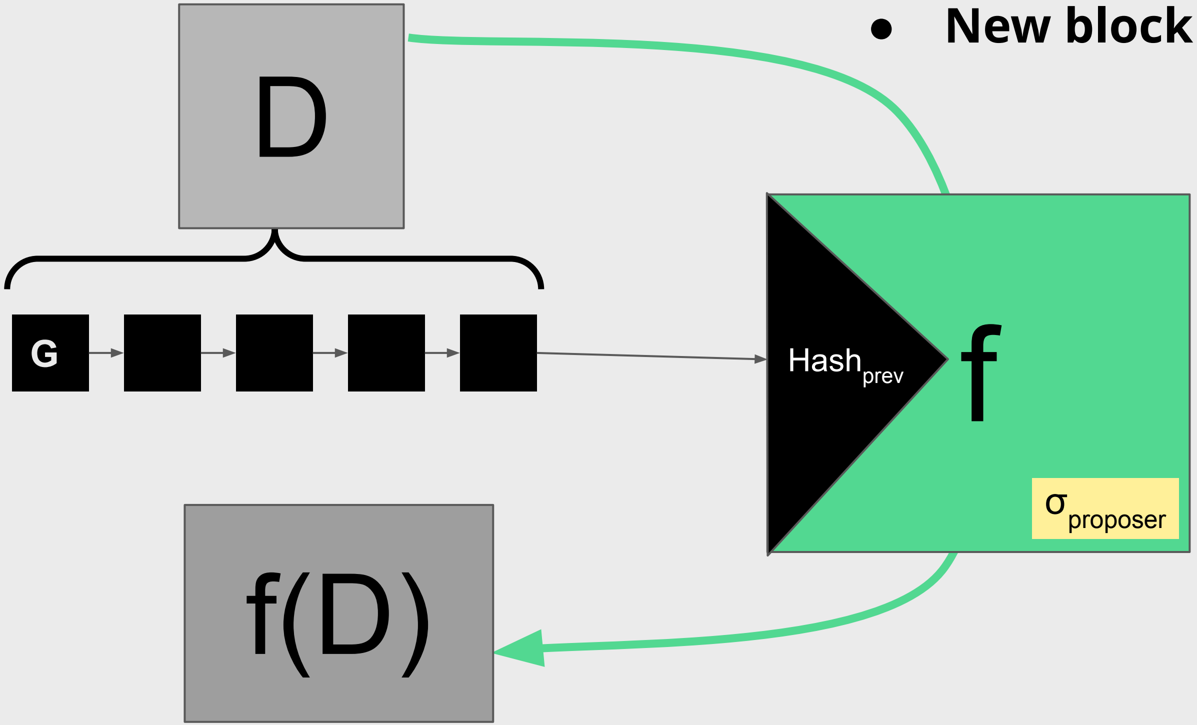
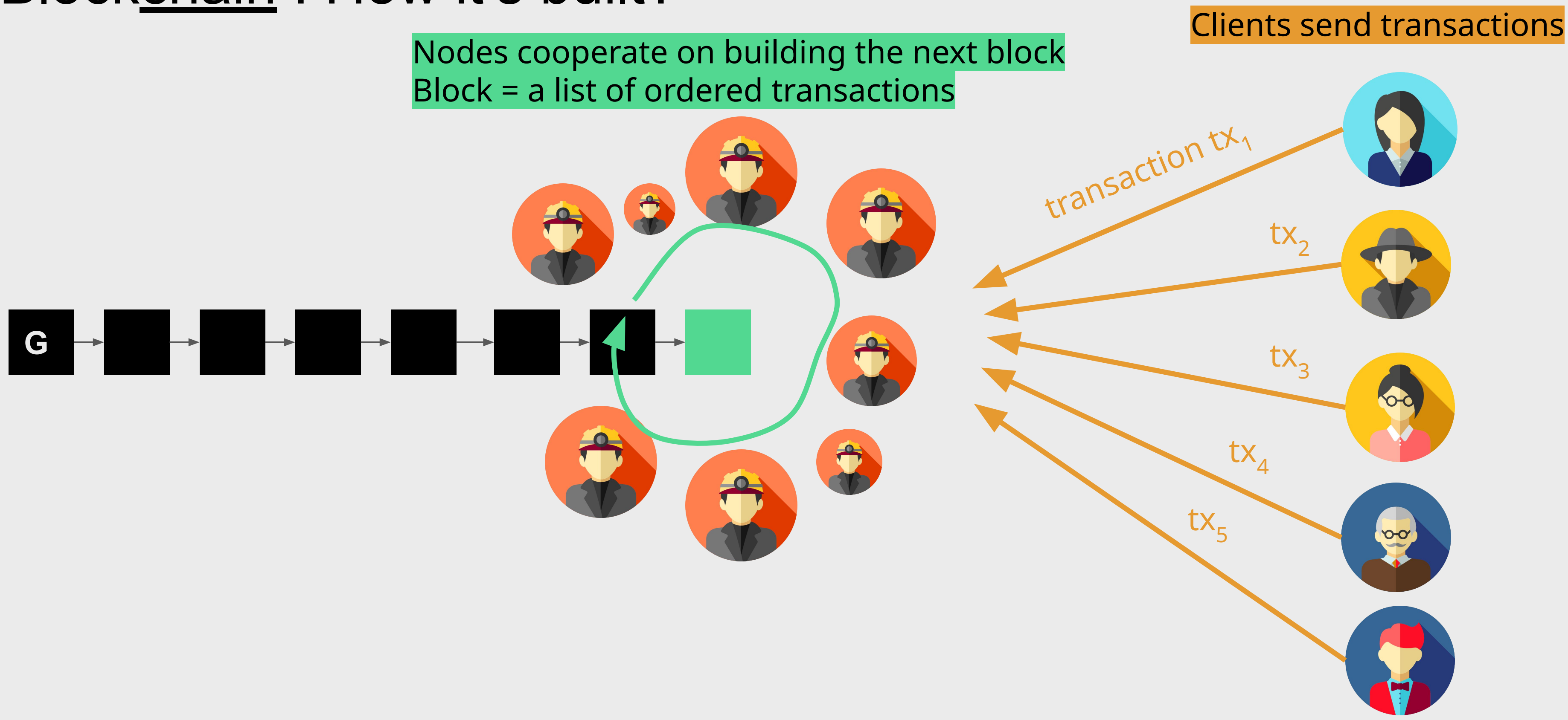
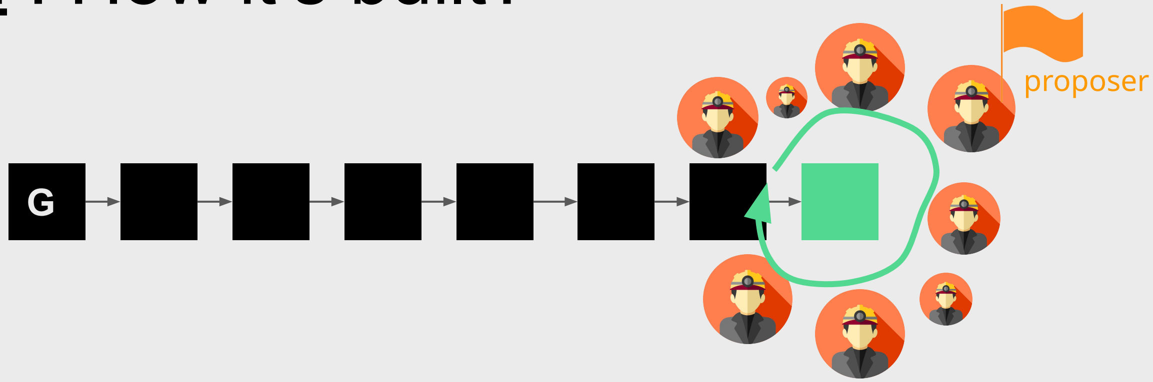


Blockchain : How it's built?



Blockchain : How it's built?



1. A proposer(s) is elected to announce a new block
   Pre-electing a proposer limits the options for Step 2

2. Everybody decides whether to accept this block or ignore

Consensus mechanism

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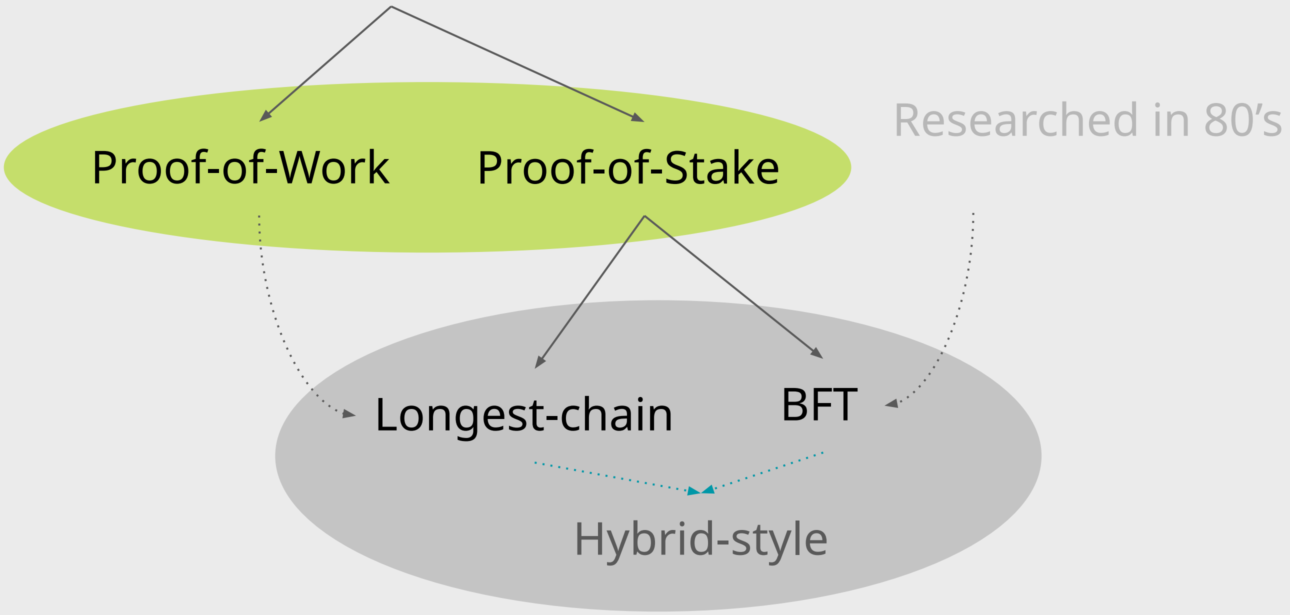
Two paradigms in blockchains



1: Proof-of-Work vs. Proof-of-Stake

for proposer election

Proof-of-Work for proposer election

- The proposer searches for a block B, s.t. **Hash(B) < target**.
    - For a hash function Hash: $\{0,1\}^* \to \{0,1\}^{256}$
    - Find B, s.t. Hash(B) < 2^{256} / D (takes time O(D) to solve)
    - D - “difficulty”
    - Currently for Bitcoin D ≈ 2^{45} a block is found once in 10 min

Proof-of-Work for proposer election

- The proposer searches for a block B, s.t. **Hash(B) < target**.
- Once found, announce B it to peers.
- Easy to verify the proposer.

Blocks are hard to find =>
small number of possible proposers

This proposer election mechanism:

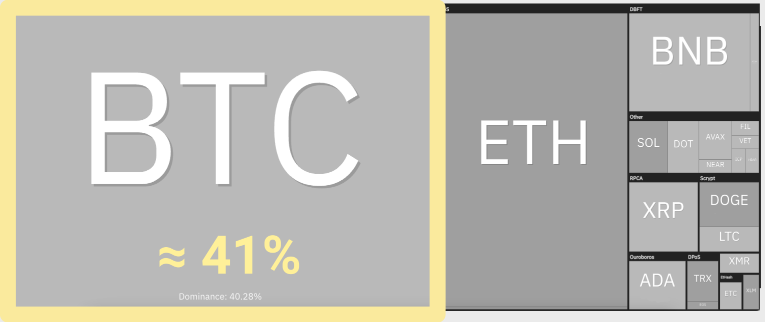
- **Live**: blocks are proposed regularly ✔
- **Fair**: each miner is elected proportional to its computational power ✔
- **Permissionless**: open participation ✔

Proof-of-Work electricity loss

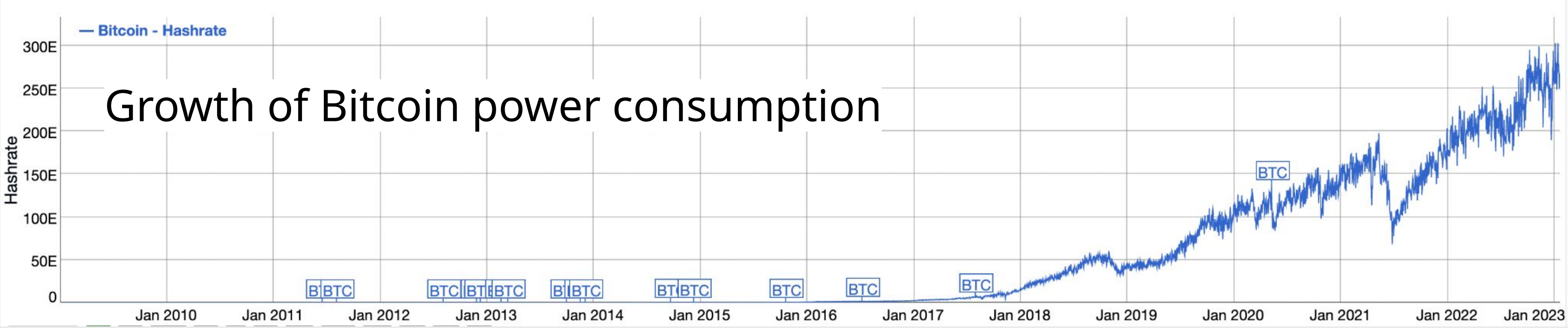
- Bitcoin: 85 TWh/yr (June 2022)
- Ethereum: 50-100 TWh/yr (June 2022)
- Argentina: 130 TWh/yr
- Mining gold: 240 TWh/yr

|Bitcoin + Ethereum| < Mining gold

Market-cap of coins:



Jan 2022, https://coin360.com/

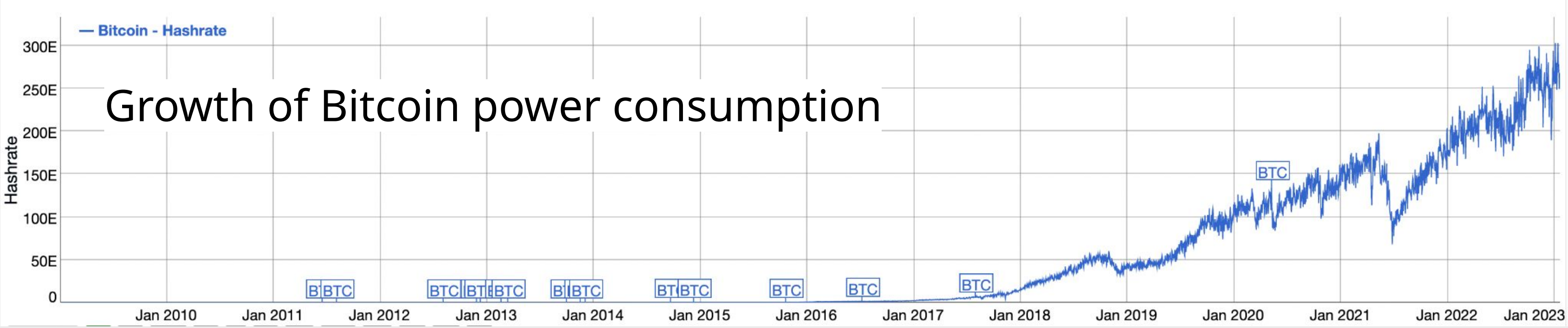


Useful number to keep in mind!

Bitcoin hash-rate:

- 200 EH/s = 2^{76} hashes per 10 min
- 6.25 BTC per block/per 10 min ≈ $150,000

2^{76} hashes per $150,000

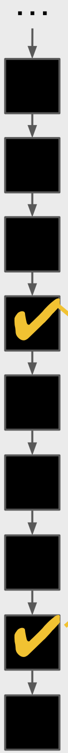


Jan 2022, https://coin360.com/

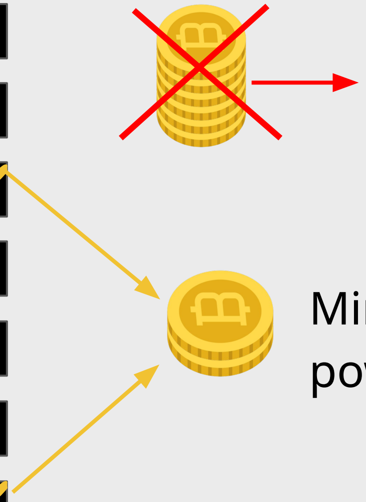
Can we make PoW better?

- Increase the block size
  - Delays in block propagation => chain will fork more => decreases reliability
- Increase the frequency of the blocks
  - Gervais et al. (CCS'16): Bitcoin block frequency can be reduced to 1 min
- Lightning network: off-chain transactions
- Change the proof-of-work puzzle
  - proof-of-**useful**-work
- Bitcoin-NG:
  - use PoW sporadically to elect the leader for a longer duration of time (to propose multiple blocks).

Proof-of-Work mining



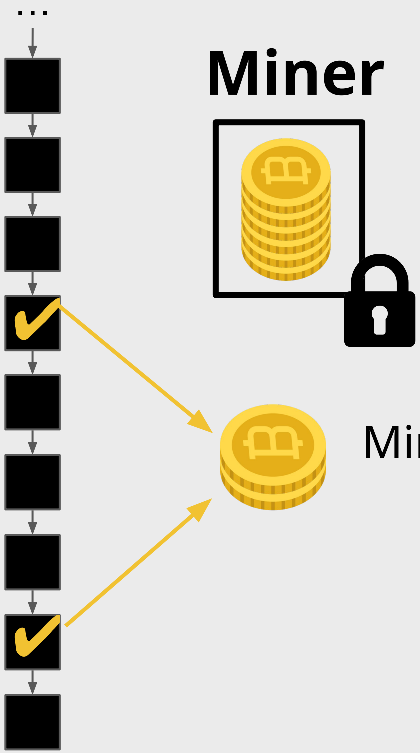
Miner



Miner spends coins for hardware and electricity.

Miner’s reward is proportional to the computational power, i.e. proportional to the money spent.

Proof-of-Stake mining



Miner locks coins.

Miner's reward proportional to the money locked.

Proof-of-Stake for proposer election

- The validator (miner) locks* T coins
- N - number of validators
- Simplest approach: round-robin
- The validator is <u>elected</u> as a proposer with probability 1/N

Desired properties:

- **Live** ✔
- **Fair** ✔
- **Permissionless**: open participation ✔?
  - Validator needs to be able to acquire coins.

* “locking” coins requires the blockchain to have basic smart-contract capabilities

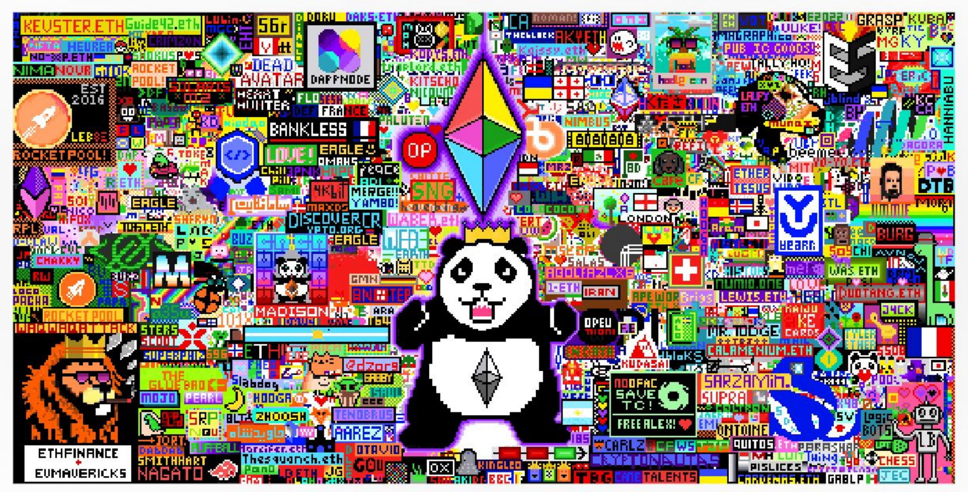
Staking design choices

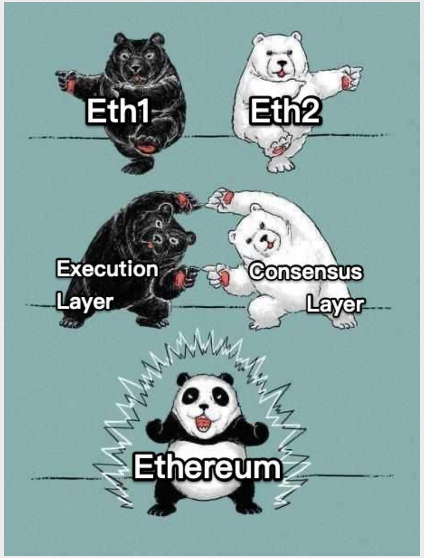
- Required coins to be locked can be
  - fixed (e.g. Ethereum 2.0: 32 ETH) or
  - variable
- Delegated-proof-of-stake : allows stakeholders delegate their stake to validators.
- Some protocols want to limit the number of validators:
  - Random selection of a subcommittee
  - Delegate stake to active nodes

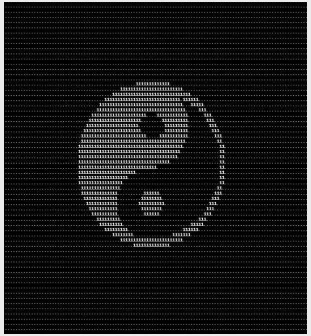
This talk: fixed staking, no delegation.

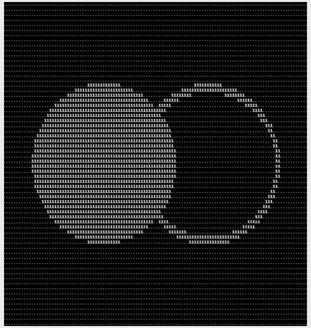
Ethereum switched from PoW to PoS

- The Merge - Sep 15, 2022
- Ethereum reduced electricity use by 30,000x
- World electricity consumption → ~99.8%

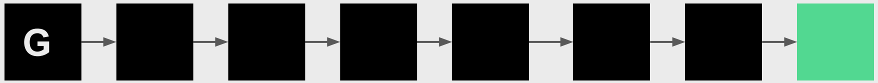








Blockchain : How it’s built?



1. A proposer(s) is elected to announce a new block
   a. Proof-of-Work or
   b. Proof-of-Stake

2. Everybody decides whether to accept this block or not
   a. Longest-chain or
   b. BFT

Consensus mechanism

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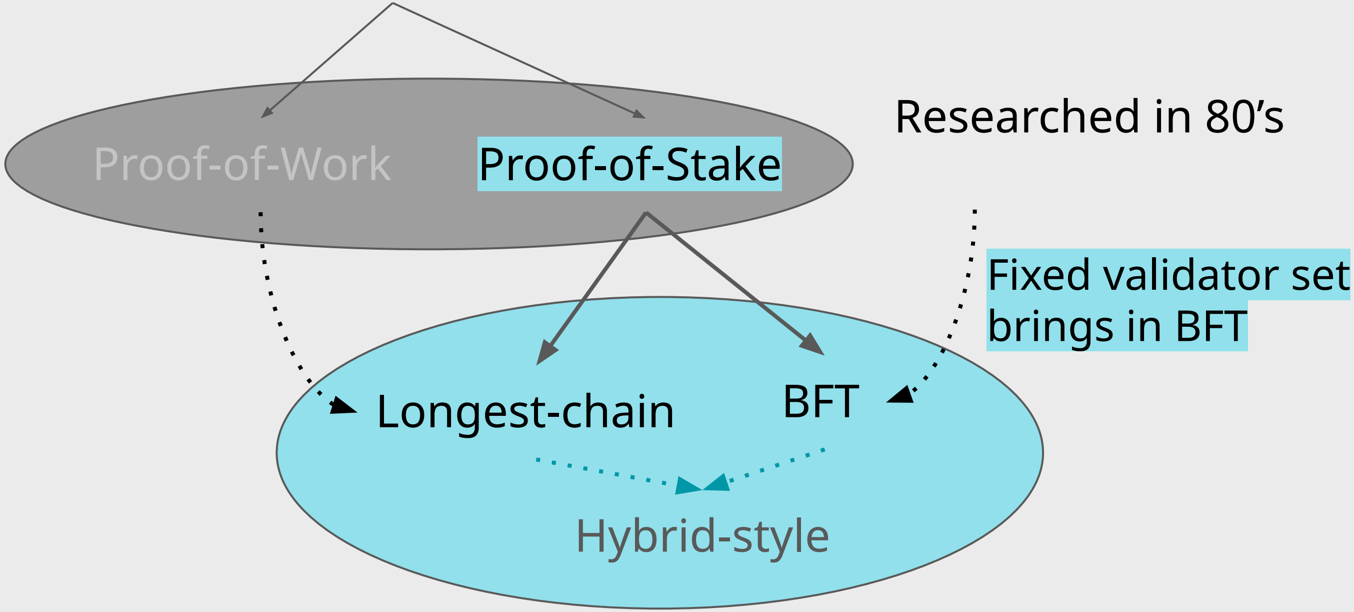
3 Research

Two paradigms in blockchains



Consensus: agree on proposed block

- **Safety**: everybody agrees on history
- **Liveness**: every valid transaction eventually gets added
- Resilience against byzantine validators
- Minimal network assumption
  - **Synchronous**: shared global clock + known bound Δ on network delay
  - **Partially-synchronous**: shared global clock + exists unknown bound Δ on network delay (equivalent: synchronous after unknown GST)
  - **Asynchronous**: no bounds on network delays (subsumes network partitions)

Possibility-Impossibility Results are well known for fixed validator set

	Liveness	**Safety**	**Byzantine threshold**
Synchrony	YES	YES	ANY* (<50%)
Partial-synchrony	YES	YES	< 33%
Asynchrony*	NO*	NO*	$\leqslant 1$
(Partial)-Synchrony with network partitions	YES	NO	1
	NO	YES	1

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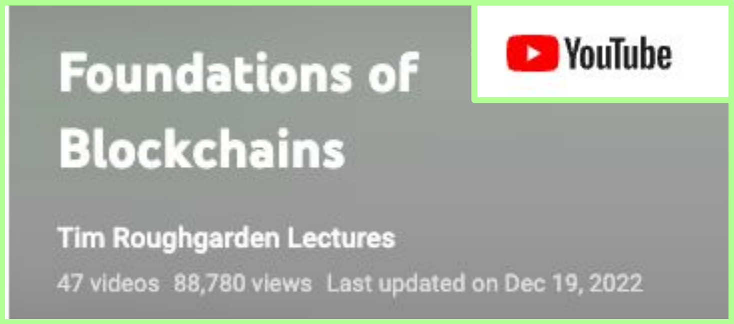
More Resources

- Youtube Lectures by Tim Roughgarden
- Consensus cannon from a16z: https://a16zcrypto.com/consensus-canon/
- Ittai Abraham: https://decentralizedthoughts.github.io/



Desired consensus properties

- **Safety**: validators agree on history
- **Liveness**: every valid transaction eventually gets added
- Resilience against **⅓ byzantine validators**
- **Partially-synchronous**: exists unknown bound Δ on network delay + shared global clock

2: Longest-chain vs. BFT consensus

Blockchains by market cap : 30

1	Bitcoin	BTC
2	Ethereum	ETH
3	Tether	USDT
4	USD Coin	USDC
5	BNB	BNB
6	Binance USD	BUSD
7	XRP	XRP
8	Cardano	ADA
9	Solana	SOL
10	Dogecoin	DOGE
11	Polkadot	DOT
12	Dai	DAI
13	Polygon	MATIC
14	Avalanche	AVAX
15	Shiba Inu	SHIB
16	TRON	TRX
17	Wrapped Bitcoin	WBTC
18	Uniswap	UNI
19	UNUS SED LEO	LEO
20	Litecoin	LTC
21	FTX Token	FTT
22	Ethereum Classic	ETC
23	Cronos	CRO
24	NEAR Protocol	NEAR
25	Chainlink	LINK
26	Cosmos	ATOM
27	Stellar	XLM
28	Monero	XMR
29	Bitcoin Cash	BCH
30	Algorand	ALGO

Jul 22, 2022 https://coinmarketcap.com/

Blockchains by market cap : 20 non-ERC-20

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Blockchains by market cap

Longest-chain PoW ,
BFT PoS ,
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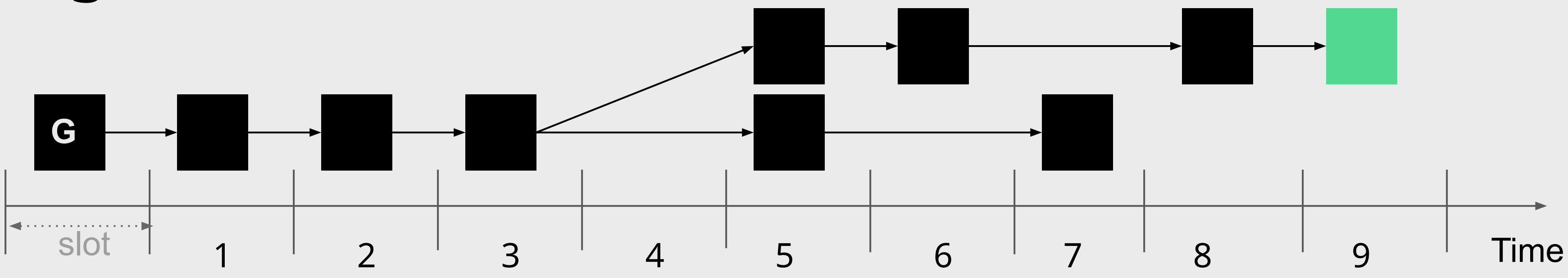
2: <u>Longest-chain</u> vs. BFT consensus

Longest-chain consensus

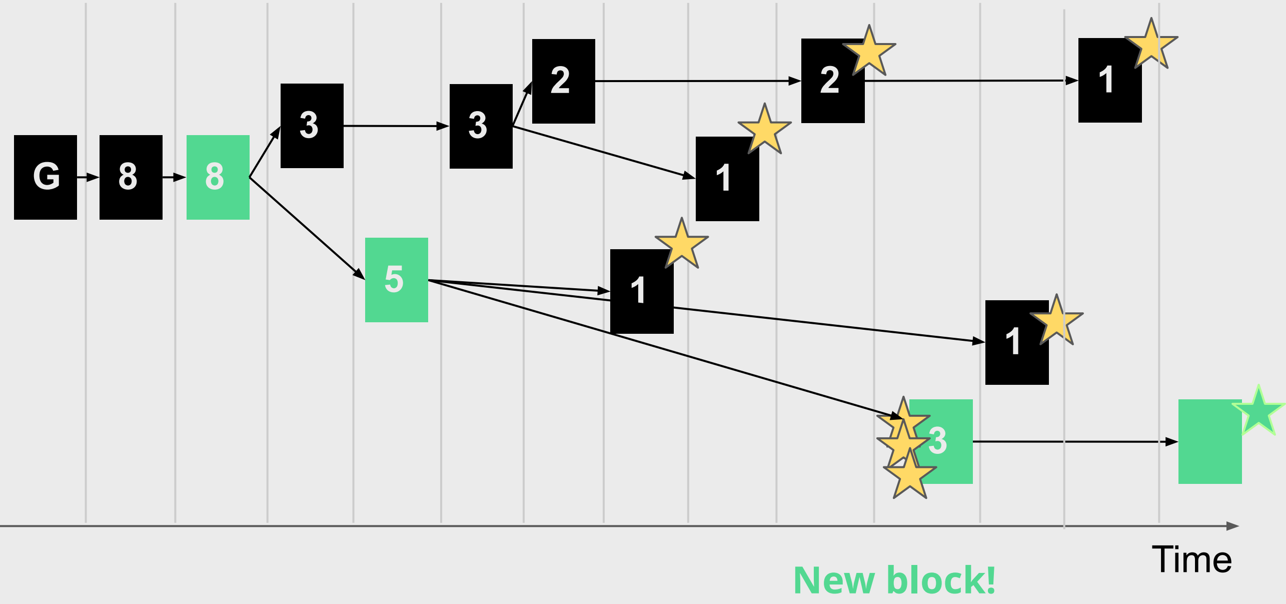


1. Each validator stores the tree of blocks.
2. Proposer is elected per slot from the validator set (can have multiple proposers).
3. Proposer picks a chain to extend according to “fork-choice rule”.
4. Creates a block on top, publishes it to the network.

Fork-choice rules: usually greedy, e.g. longest (more blocks in it)
Parameters are tuned so that with high probability only one chain **eventually** wins.

Ethereum's fork-choice rule "LMD GHOST":

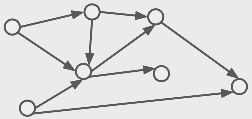
grows the blockchain on sub-branches with the "most activity".



<u>LMD GHOST:</u>

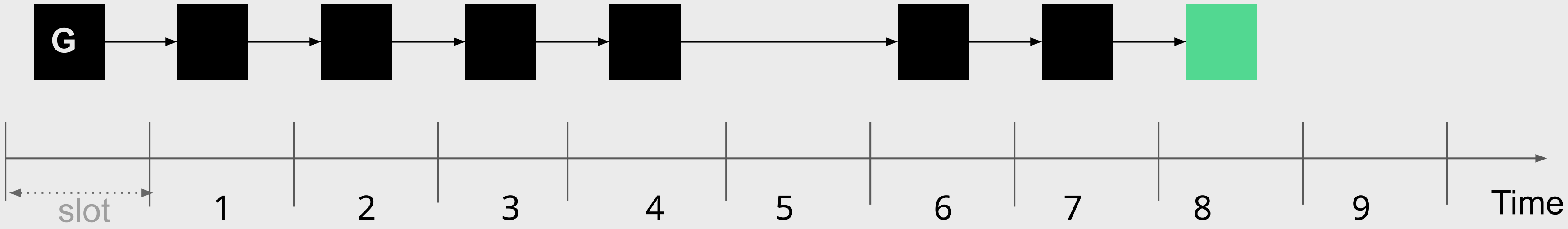
- One leader is selected per slot to propose a block.
- Each validator votes once in an epoch (32 slots) at its designated slot.
- Latest vote ★ per validator is counted.
- The number on each block is the number of validators' votes on the subtree.
- The greedy algorithms walk the tree choosing the "heaviest" blocks.

Most popular PoS approaches

	Longest-chain consensus
Examples:	Ethereum,Peercoin,Ouroboros
Finality:	Eventual = Probabilistic
Safety under partition:	NO
Liveness under partition:	YES
#validators:	unlimited
Typical network topologies:	Flexible: 

2: Longest-chain vs. BFT consensus

BFT-consensus

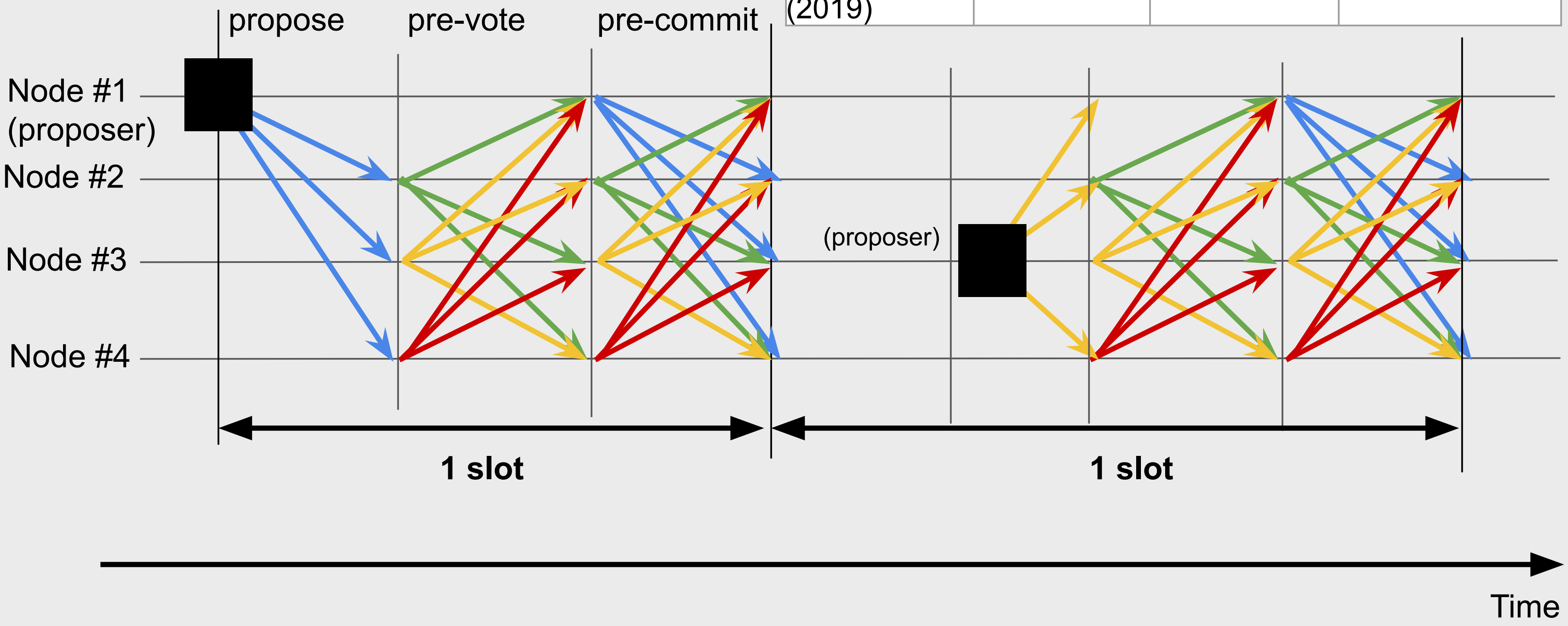


Each slot:

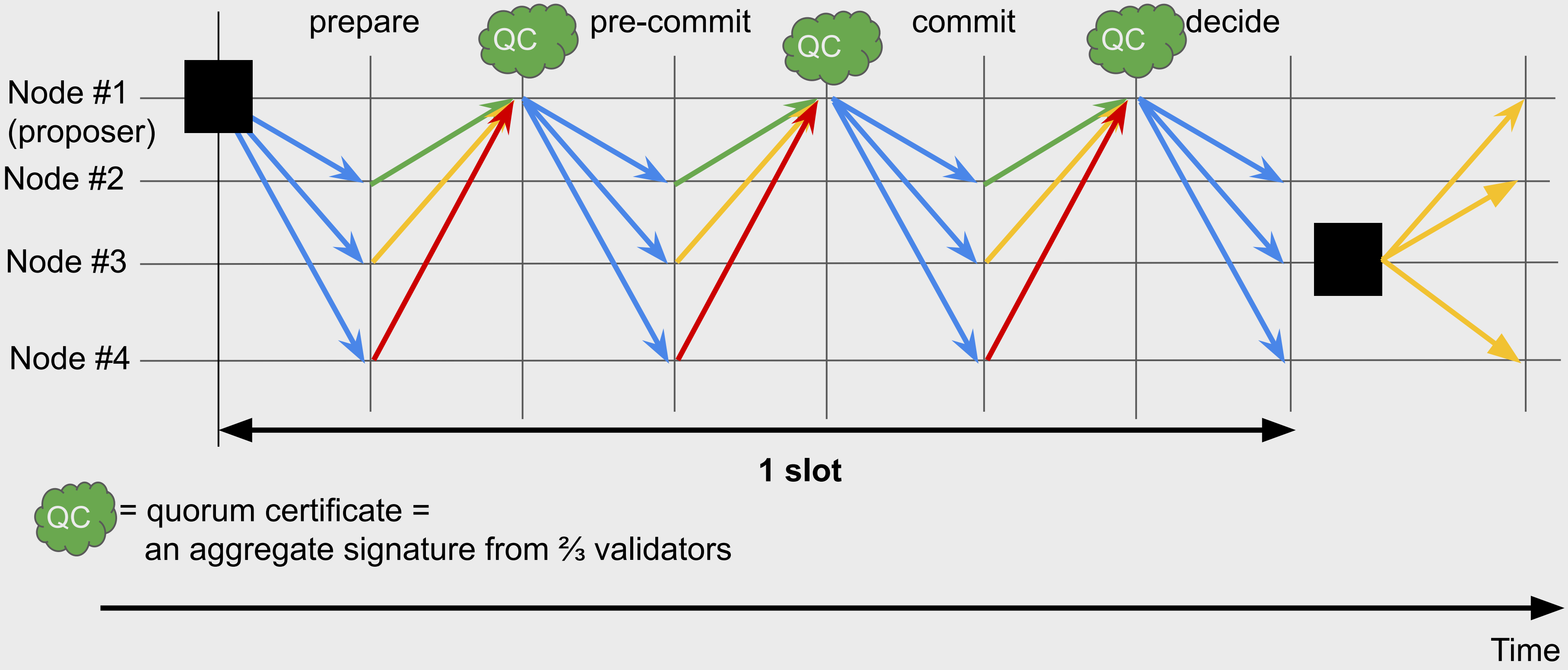
1. A proposer is elected from the validator set.
2. The proposer proposes a new block.
3. Validators work on finalizing the block, it either gets finalized or not.

Tendermint BFT (2016)

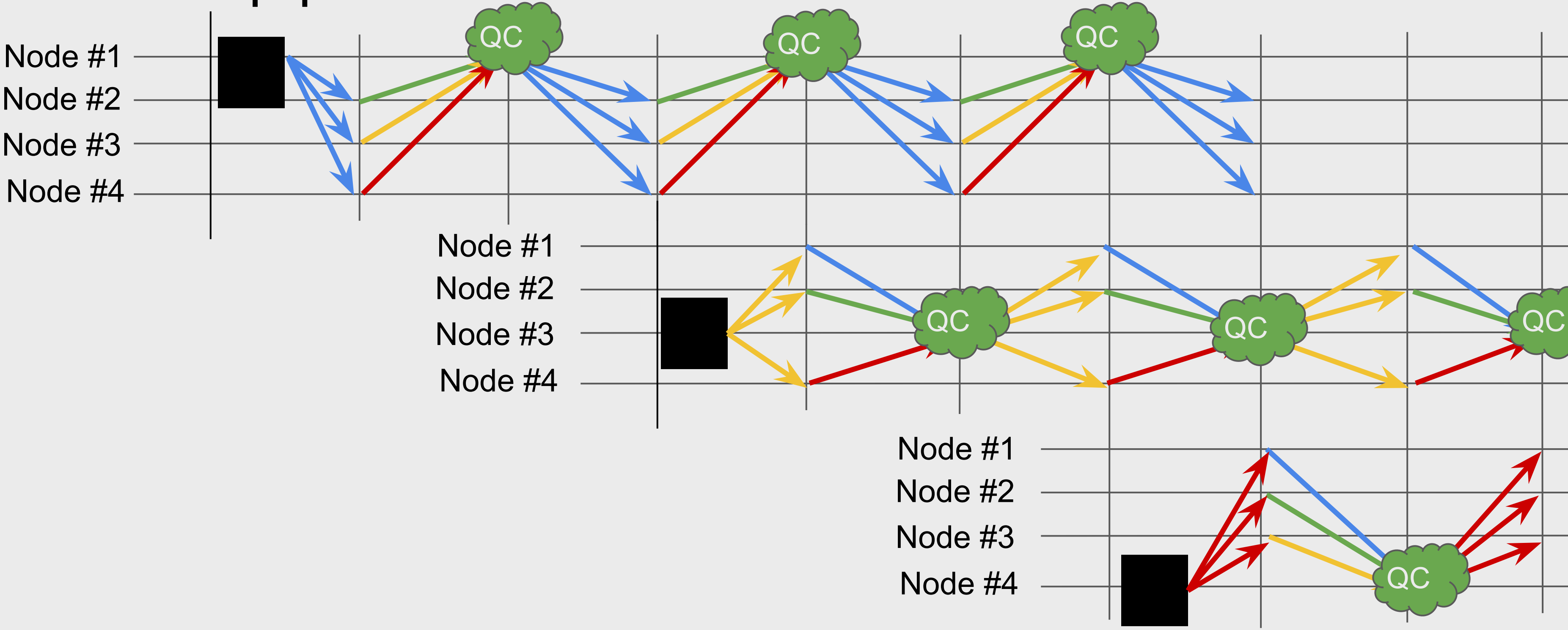
	Correct proposer	Proposer failure	Responsiveness
Tendermint (2016)	$O(n^2)$	$O(n^2)$ / $O(n)$	✗
HotStuff (2019)	$O(n)$	$O(n)$	✓



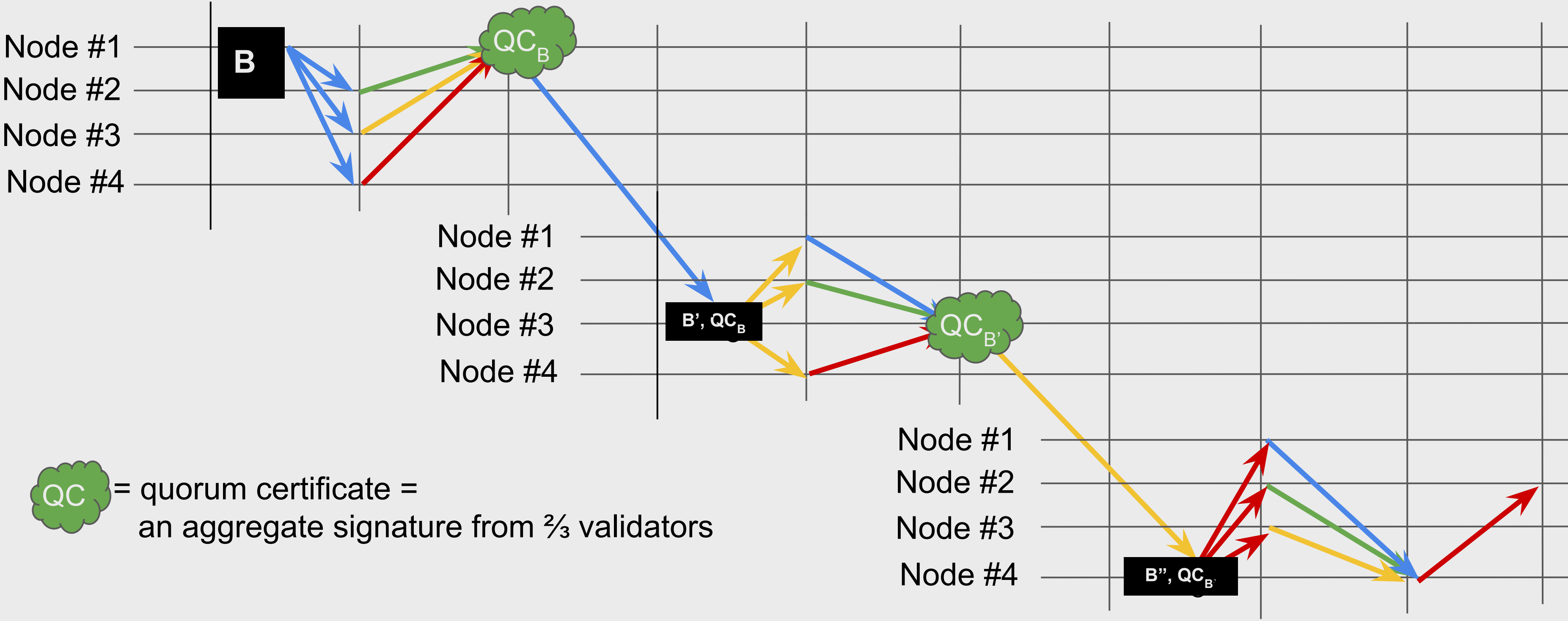
Hotstuff: rerouting through the proposer and use aggregatable signatures



Hotstuff pipelined

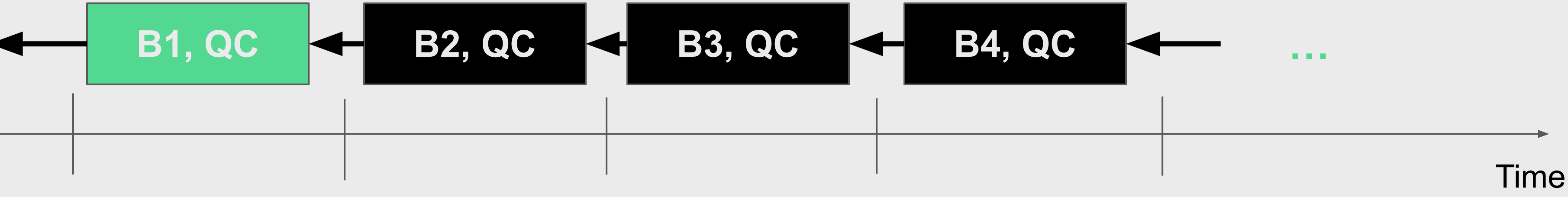


Hotstuff pipelined



= quorum certificate =
an aggregate signature from ⅔ validators

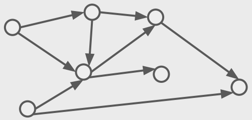
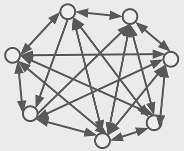
HotStuff: 3-chain commit rule



Hotstuff: B_1 gest committed after there are <u>three</u> blocks with QCs on top of it.

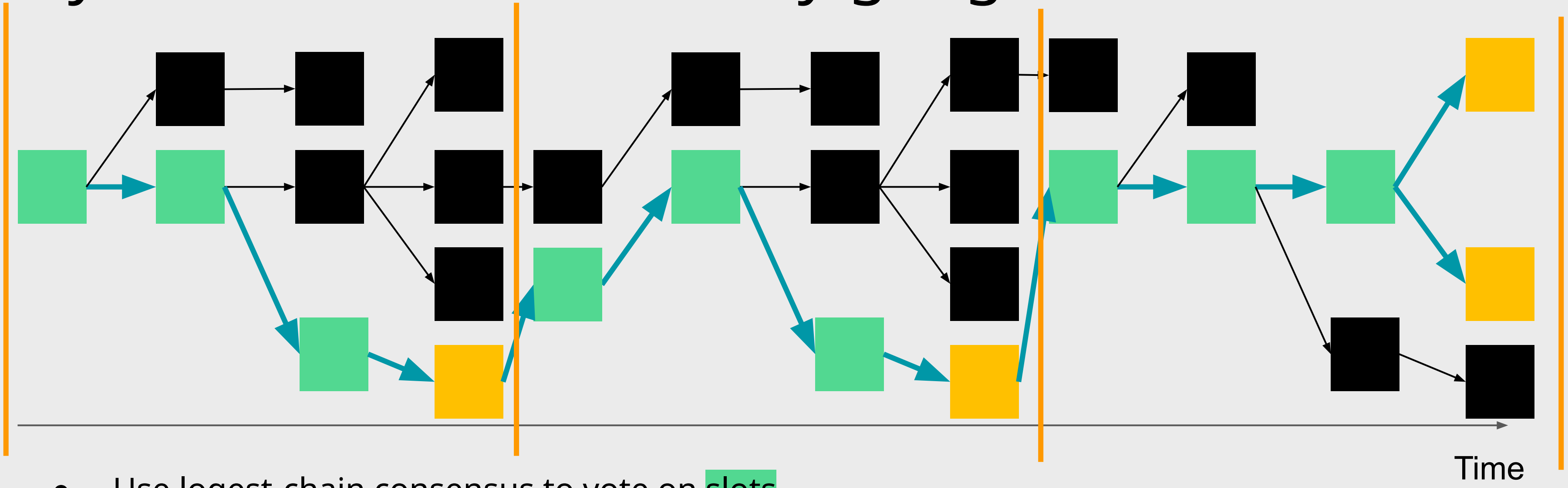
https://malkhi.com/posts/2019/08/hotstuff-three-chain-rules/

Most popular PoS approaches

	Longest-chain consensus	BFT consensus
Examples:	Peercoin, Ouroboros-*	Tendermint, Hotstuff
Finality:	Eventual = Probabilistic	Deterministic Immediate
Safety under partition:	NO	YES
Liveness under partition:	YES	NO
#validators:	unlimited	4-100 slower with more validators
Typical network topologies:	Flexible: 	Complete: 

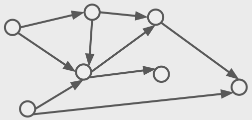
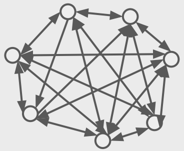
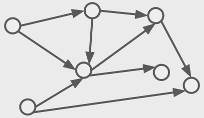
3: Hybrid consensus: Longest-chain + BFT

Hybrid-consensus / finality gadgets



- Use logest-chain consensus to vote on slots
- Use BFT consensus to vote on epochs
- Epoch is a fixed number of slots
    - Ethereum: 32 slots per epoch, 12 second per slot, 6.4 min per epoch
- Typically: 2-stage BFT voting, hence 2 epochs to finality

Most popular PoS approaches

	Longest-chain consensus	BFT consensus	Hybrid
Examples:	Peercoin, Ouroboros-*	Tendermint, Hotstuff	
Finality:	Eventual = Probabilistic	Deterministic Immediate	Deterministic Slow
Safety under partition:	NO	YES	YES
Liveness under partition:	YES	NO	TEMPORAL LOSS
#validators:	unlimited	4-100 slower with more validators	unlimited
Typical network topologies:	Flexible: 	Complete: 	Flexible: 

Algorand : multiple leaders per slot

- No locked tokens, **no slashing**. A user registers a participation key for a certain number of rounds.
- Each node runs a VRF privately twice:
  - to determine whether it is elected as a leader, and
  - to determine whether it is elected in a committee (new committee is selected for every step).
- There could be multiple leaders per round
- Similar to longest-chain: the lowest block (by hash) is propagated.
- Committee then votes twice on the block (in BFT-style).
- Forward-secure: nodes discard old keys disabling attacks on the past.
- Network-partition-resilient: halts during the partition, resumes when the network is restored.

2: Longest-chain vs. BFT consensus

more...

Avalanche : leaderless consensus

- Snowball/Snowman leaderless consensus protocol!
- UTXO model, thus txs form a DAG.
- Establishes a partial order.
- Each node accepts a valid transaction tx_1 and sends it to other nodes, until it sees a conflicting transaction, tx_2. If it hears about tx_2 from a > threshold of peers, it switches tx_1 to tx_2 and sends that to its peers.
- Finality: probabilistic

Disclosures

Thank you!

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