State Machine Replication Among Strangers, Fast and Self-Sufficient

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CRYPTO '25

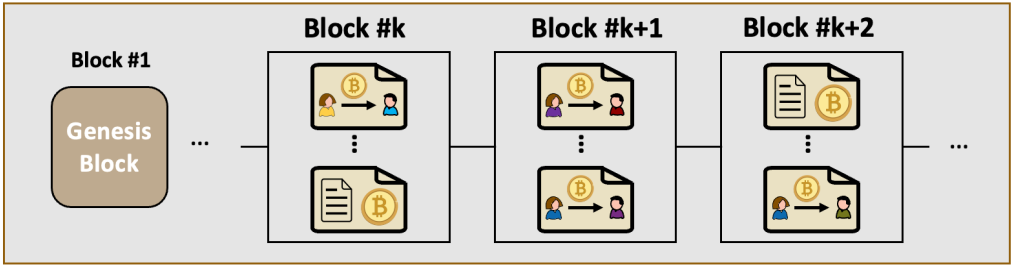
[1]Texas A&M University, [2]University of Edinburgh, [3]IOG

Juan Garay[1], Aggelos Kiayias[2,3], **Yu Shen**[2]

"Among Strangers" (a.k.a. The Permissionless Model)

- The "traditional" distributed system.
  - Nodes are known **a priori**.
  - As in most deployed networks of computers.
- The "permissionless" model.
  - Nodes do **NOT** know each other (not even their exact number!)
  - Nodes come and go.
  - **Anyone** can join.

Blockchains (Ledger Consensus/State Machine Replication)



- **Consistency:** $\forall i, j \in \mathcal{H}, t \leq t' : \mathsf{Log}_i[t] \preceq \mathsf{Log}_j^*[t']$.
- **Liveness:** $(\forall i \in \mathcal{H} : \mathsf{tx} \in \mathsf{I}_i[t]) \implies (\forall i \in \mathcal{H} : \mathsf{tx} \in \mathsf{Log}_i[t+u])$.[1]

[1] $\mathsf{Log}_j[t]$ = Log of P_i at time t; $\mathsf{Log}_i^*[t]$ = with transactions in progress. $\mathsf{I}_i[t]$ = transaction input of P_i at time t consistent with $\mathsf{Log}_i[t]$.

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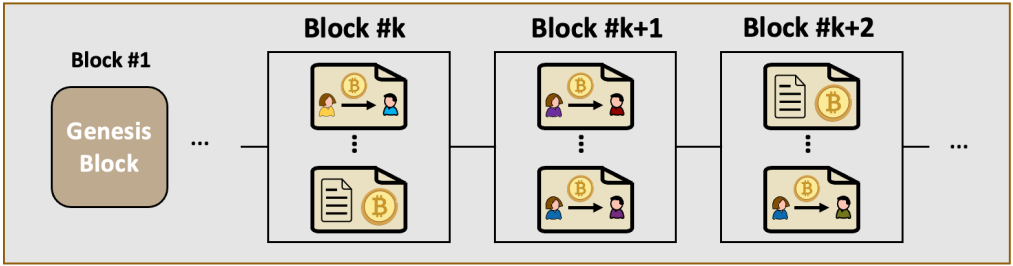

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- More properties are of interest: fast settlement, fairness, self timekeeping, etc.

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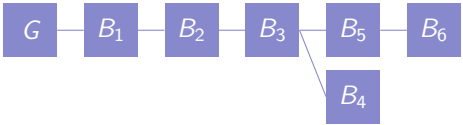
Transaction Settlement Time

- Honest parties ("miners") always choose the **longest** (heaviest) chain they received.
  - If a party wants to **erase** a transaction, it has to find a longer chain!
  - If transaction is "**sufficiently deep**," it cannot do this unless it has a "majority of hashing power."



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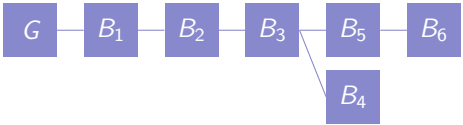

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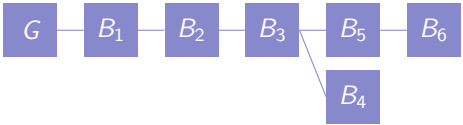

- For example, Bitcoin transactions are considered as settled after **6** blocks.
- To be **cryptographically secure**, transactions are settled after $\mathrm{polylog}(\kappa)$ rounds [GKL17].
- *Permissioned* SMR protocols can achieve (expected-)constant settlement time (i.e., "fast").

Fairness in Accessing SMR

- An intriguing question: Who can insert symbols to the permissionless SMR?
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  - Network delay can create forks.
  - Malicious parties can discard honest blocks (e.g., block withholding attacks).
  - Bitcoin has bad "chain quality" (cf. [GKL15]).

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- **Fast Fairness:** Fairness in expected-constant time.

"Self-Sufficient" Protocols

- Hardware clocks are **drifting** clocks.
  - Crystal oscillator drfits by 10 seconds within a day/week/month.
  - Network time protocol (NTP) is typically adopted to synchronize software clocks ("global clock").

https://commons.wikimedia.org/w/index.php?curid=31253284

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- An SMR protocol is said to be **self-sufficient** if it keeps its own time under the mere assumption that parties have drifting local clocks.

Clocks in Bitcoin

- Bitcoin miners use their system clock (synced by NTP) to insert block timestamps.
- If system clock is out-of-sync (when difference from **median** peer clocks exceeds 10 minutes), a warning[2] is pop-up for human operator.

```
bilingual_str msg{strprintf(_(
    "Your computer's date and time appear to be more than %d minutes out of sync with the network, "
    "this may lead to consensus failure. After you've confirmed your computer's clock, this message "
    "should no longer appear when you restart your node. Without a restart, it should stop showing "
    "automatically after you've connected to a sufficient number of new outbound peers, which may "
    "take some time. You can inspect the `timeoffset` field of the `getpeerinfo` and `getnetworkinfo` "
    "RPC methods to get more info."
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→ Bitcoin is **NOT** self-sufficient.

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Prior Work

- **Fast settlement**
  - ○ Fast settlement for **non-conflicting** transactions (Prism [Bag+19], Ledger Combiner [Fit+20]).
  - ✗ Slow settlement for **conflicting** transactions (Smart contract, **Bitcoin Script**).
- **Fast fairness**
  - ✗ Fairness in polylog(κ) rounds (Fruitchain [PS17]).
- **Self Timekeeping**
  - ✗ Clock synchronization with **imperfect** clocks (Timekeeper [GKS22]).

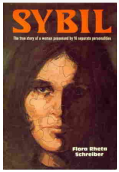
[Bag+19] Vivek Kumar Bagaria, Sreeram Kannan, David Tse, Giulia C. Fanti, and Pramod Viswanath. "Prism: Deconstructing the Blockchain to Approach Physical Limits". CCS '19.

[Fit+20] Matthias Fitzi, Peter Gazi, Aggelos Kiayias, and Alexander Russell. "Ledger Combiners for Fast Settlement". TCC '20.

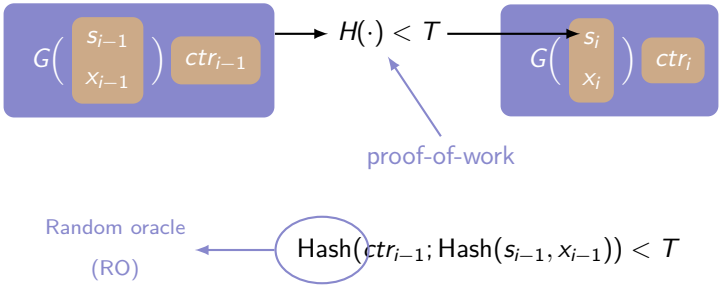
[PS17] Rafael Pass and Elaine Shi. "FruitChains: A Fair Blockchain". PODC '17.

[GKS22] Juan A. Garay, Aggelos Kiayias, and Yu Shen. "Permissionless Clock Synchronization with Public Setup". TCC '22.

Proofs of Work (aka "Crypto Puzzles")

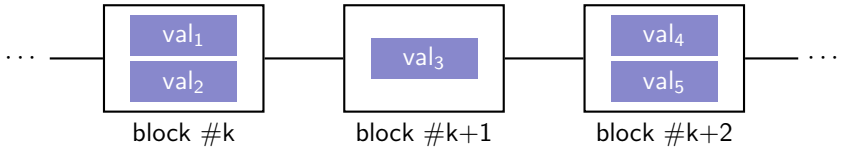


- Moderately hard functions: Spam mitigation, denial of service protection, ...
- Most impactful application: Design of blockchain protocols such as Bitcoin



1/2 Consensus (a.k.a. BA) Protocol [GKL15]

- Parties mine PoWs for each **block** — as in standard Bitcoin backbone protocol.
- Parties mine PoWs for each **input** (value + nonce); they keep transmitting **"PoW-ed" inputs** until they are recorded on chain.



- After the blockchain grows sufficiently, chop off the last $\mathrm{polylog}(\kappa)$ blocks and return the **median** value among unique inputs in the common prefix.

[GKL15] Juan A. Garay, Aggelos Kiayias, and Nikos Leonardos. "The Bitcoin Backbone Protocol: Analysis and Applications". Eurocrypt '15.

2x1 PoWs: Composition of PoW-based Protocols

Naïve double PoW (Not secure!)

$h \leftarrow G(x, s)$
if $H(h, ctr) < T$ then ...

$h' \leftarrow G(x', s')$
if $H(h', ctr') < T'$ then ...

Given $((x, s), ctr)$
Verify $H(G(x, s), ctr) < T$

Given $((x', s'), ctr')$
Verify $H(G(x', s'), ctr') < T'$

2×1 PoW

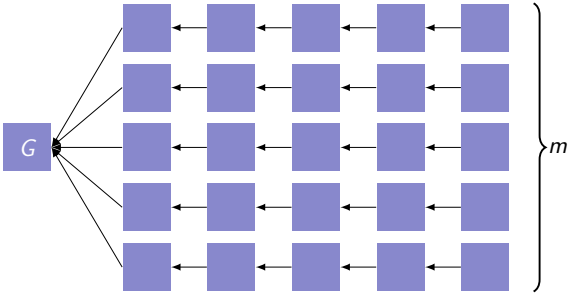
$h \leftarrow G(x, s)$
$h' \leftarrow G(x', s')$
$w \leftarrow H(h, h', ctr)$

if $w < T$ then ...
if $[w]^{\mathrm{R}} < T'$ then ...

Given $((x, s), (*, *), ctr)$
Verify $H(G(x, s), G(*, *), ctr) < T$
Given $((*, *), (x', s'), ctr')$
Verify $H(G(*, *), G(x', s'), ctr') < T'$

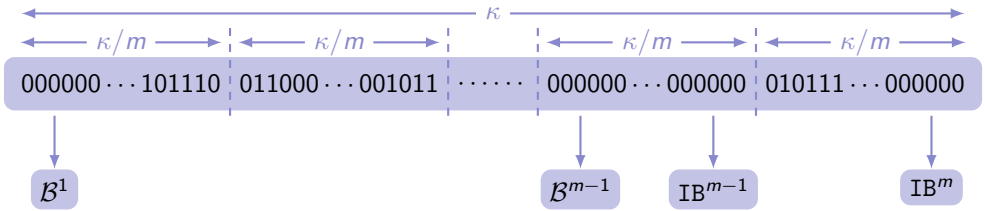
Parallel Blockchains

- **Basic Idea:** Extend 2×1 PoW to m×1 **PoW**.
- Fully independent when $m = \Theta(\text{polylog}\kappa)$.



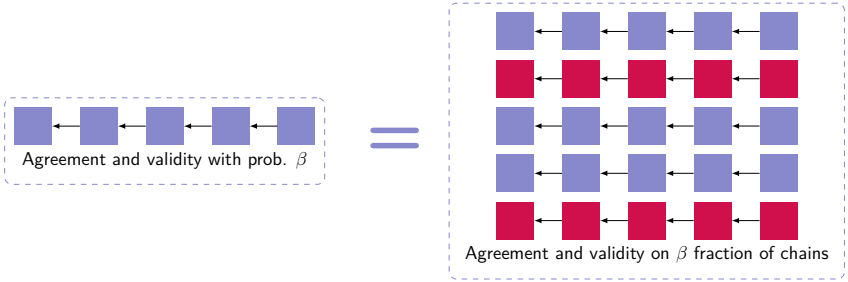
Parallel Blockchains (Cont'd)

- **Basic Idea:** Extend 2×1 PoW to m×1 **PoW**.
- Fully independent when $m = \Theta(\text{polylog}\kappa)$.
- We can run PoW BAs in parallel.
  - 2×1 PoW (block + transaction) in each instance.



Phase-based Parallel Chains

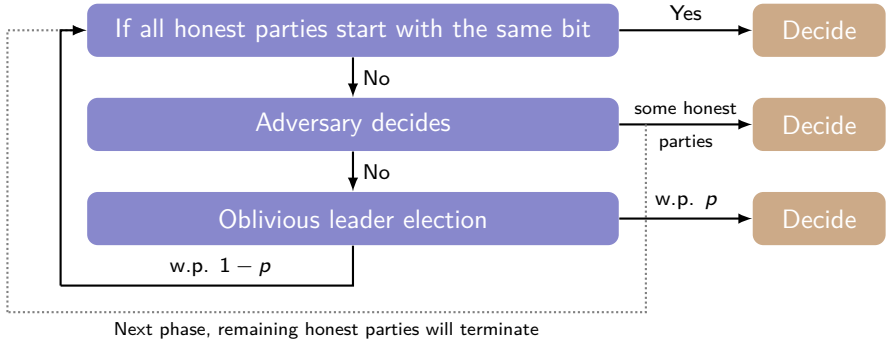
- In [GKL15] (honest-majority PoW consensus in polylog(κ) rounds):
  - Agreement and validity with **overwhelming** prob. after polylog rounds.
  - Agreement and validity with **constant** prob. after **constant** rounds.
- With sufficently many parallel chains:



[GKL15] Juan A. Garay, Aggelos Kiayias, and Nikos Leonardos. "The Bitcoin Backbone Protocol: Analysis and Applications". Eurocrypt '15.

King Consensus [BGP89; FG03]

- Proceeds in phases until termination (In each phase each party has an input bit).



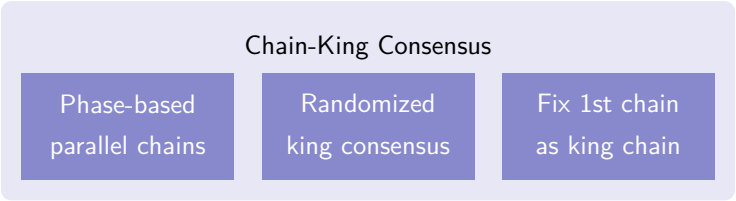
Chain-King Consensus [GKS24]

- Oblivious leader election (OLE) using only RO?
- A simple construction: Fix the **1st chain** as the "King Chain".

[GKS24] Juan A. Garay, Aggelos Kiayias, and Yu Shen. **"Proof-of-Work-Based Consensus in Expected-Constant Time"**. Eurocrypt '24.

Chain-King Consensus [GKS24]

- Oblivious leader election (OLE) using only RO?
- A simple construction: Fix the **1st chain** as the "King Chain".
- With parallel chains, adversary power is "**diluted**" so that he cannot always win on a specific chain.



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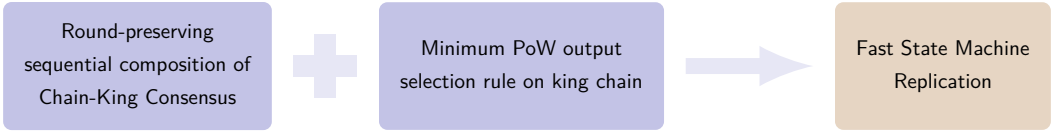
Permissionless SMR with Fast Settlement

- Decide output of king chain using input-block with minimum PoW (smallest hash).
  - With **constant prob.**, an invocation of chain-king consensus outputs a batch of transactions proposed by **honest parties**.



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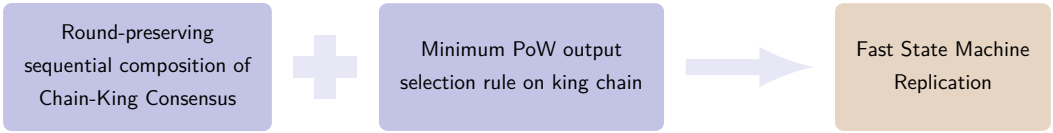

- A few more things have been done here:
  - Extended the above protocol to the **variable** difficulty setting.
  - A bootstrapping algorithm to help fresh parties "catch-up" in **constant** time.

Fast Fairness

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Fast Fairness

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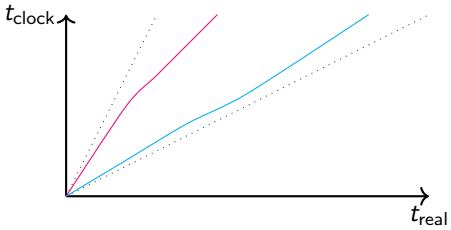
- A "pre-agreement" on coinbase transactions suffices to achieve fast fairness.
  - In the first phase in Chain-King Consensus, parties use 2×1 PoW to mine their own coinbase trasnactions, submit them to the **first** chain.
  - By the end of the phase, parties stick to the coinbase transaction with **minimun hash** in the first chain their local view.
  - Then, a new invocation of Chain-King Consensus starts at the second phase.
- For any party P with p% computational power...
  - With probability p%, P produces the coinbase transaction with minimum hash.
  - With probability $(1 - \epsilon)$, parties agree on P's coinbase transaction on the first chain.

Self Sufficiency

- An SMR protocol is said to be **self-sufficient** if it keeps its own time under the mere assumption that parties have drifting local clocks.

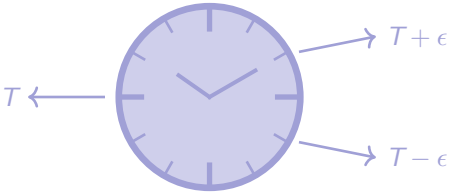


- **Assumption:** Hardware clocks run within a linear envelope[3] of real time.

[3] A function $f : \mathbb{R} \to \mathbb{R}$ is within a (U, L)-linear envelope if and only if it holds that $L \cdot x - c \leq f(x) \leq U \cdot x + c$.

Clock Synchronization

- **Bounded Skew:** Honest parties maintain close logical clocks.
- **Accuracy:** Honest parties report logical time within a linear envelope of the real time.



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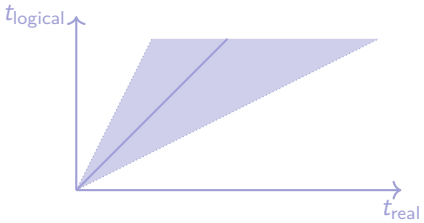
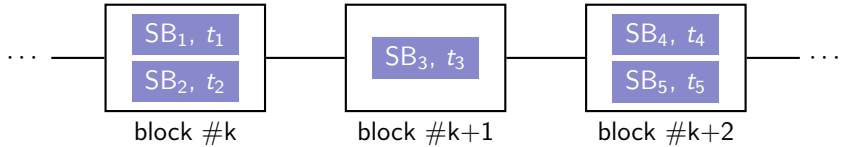


Accuracy

Clock Adjustment Algorithm

- Honest-majority PoW-based BA can be extended to timekeeping [GKS22].
  - Inputs record also timestamps (now we call them "synchronization beacons").
  - Parties bookkeep the local arrival time for each beacon.



	SB_1	SB_2	SB_3	SB_4	SB_5
P	t'_1	t'_2	t'_3	t'_4	t'_5

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Clock Adjustment Algorithm (Cont'd)

- At the end of an interval, parties adjust their local clocks:
  - Compute the difference between timestamp and local arrival time for each beacon on chain.
  - Add the **median** of their differences to local time.

$$\text{new-clock} = \text{old-clock} + \mathbf{med}\{\text{SB}.\mathit{timestamp} - \text{SB}.\mathit{arrivalTime} \mid \text{SB} \in \mathcal{C}\}$$

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- ✗ This does **NOT** work with **drifting** clocks!
  - To agree on beacons, interval duration needs to be set as $\text{polylog}(\kappa)$
  - → With drifting clocks, skew $= \Theta(\text{polylog}(\kappa))$.
  - It only works for imperfect clocks (cf. [Bad+21; GKS22]).

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- **Solution:** Use parallel blockchains to acquire a set of clock values in **constant** time, where a large fraction of them are "good."

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- **Example 1:** Malicious parties suggest crazy clock values.

- **Solution*:** Prune the η largest and smallest clocks.
- **Example 2:** Malicious parties suggest confusing clock values.

Clock Synchronization (Cont'd)

- **Solution:** Apply **Approximate Agreement** [Dol+86] over the set of clock values.
  1. **Reduce:** Remove the η largest and smallest elements.
  2. **Select:** Divide the remaining clocks into chunks of η elements; for each chunk, select a representative (the first element).
  3. Return the **average** over clock representatives.

[Dol+86] Danny Dolev, Nancy A. Lynch, Shlomit S. Pinter, Eugene W. Stark, and William E. Weihl. "Reaching approximate agreement in the presence of faults". J. ACM.

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- **Result:** Clocks with **bounded skews** (linear w.r.t. network delay and clock drfit rate).

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Takeaways

In the permissionless PoW setting with drifting clocks, we achieve:

- **Fast Settlement**
  - **All** incoming transactions are confirmed in expected-constant time.
- **Fast Fairness**
  - A coinbase transaction, selected w.p. proportional to computational power, is introduced every expected-constant-time interval.
- **Self-Sufficient Timekeeping**
  - Protocol participants maintain bounded skews.
  - State machine exports an accurate SMR time w.r.t. real time.

Thank You

[GKS25] https://ia.cr/2025/616

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