SocChain: Blockchain with Swift Proportional Governance for Bribery Mitigation

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ABSTRACT
Blockchain governance is paramount to lead securely a large group of users towards the same goal without disputes about the legitimacy of a blockchain instance over another. As of today, there is no efficient way of protecting this governance against an oligarchy. This paper aims to offer a new dimension to the security of blockchains by defining the swift proportional governance problem. This problem is to rapidly elect governance users that proportionally represent voters without the risk of dictatorship. We then design and implement an open permissioned blockchain called SocChain (Social Choice Blockchain) that mitigates bribery by building upon results in social choice theory. We deploy SocChain and evaluate our new multi-winner election DApp running on top of it. Our results indicate that, using our DApp, 150 voters can elect a proportionally representative committee of 150 members within 5 minutes. Hence we show that SocChain can elect as many representatives as members in various global organizations.

1 INTRODUCTION
This paper aims to offer a new dimension to the security of blockchain [52] by introducing a framework to define, solve and evaluate a swift proportional governance as the problem of electing rapidly a committee that proportionally represents voters, to cope with bribery and dictatorship.

The notion of governance, which is generally understood as the processes relied upon to make decisions and modify the protocol, has become an important topic in blockchain [14, 51, 75]. The absence of governance already led users to create dissident instances of the two largest blockchains [42, 68]. The worst thing that can happen is when an attacker takes control of the governance, which is best addressed through decentralization. Recent efforts were already devoted to applying social choice theory to distributed systems to cope with a fixed coalition of malicious users, also called a byzantine oligarchy [76]. Yet, such solutions do not rotate the governance and fail as soon as the attacker manages to bribe a third of the governance.

A pernicious threat is thus the risk of obtaining an oligarchy that acts as a dictator. The Proof-of-Stake (PoS) design that favors wealthy participants over others gained popularity as an efficient replacement to Proof-of-Work (PoW) in blockchain designs. Combined with the Pareto Principle [53] stating that few users own most of the resources of the system or with bribery as the act of offering something to corrupt a participant, the system may end up being governed by an oligarchy. Of course, no blockchains can be implemented if an adversary is capable of bribing all nodes instantaneously, this is why a slowly adaptive adversary is generally assumed by blockchains [36, 45, 74]. Assuming that bribing takes time is reasonable [49]: Typically, a user can easily bribe a close friend but will take more time to bribe an acquaintance and may even fail at bribing a stranger (due to the fear of being exposed as corruptible). But even under this assumption, the risk of an oligarchy remains.

Hence, blockchains require a fast governance reconfiguration that counteracts a growing coalition of malicious nodes by selecting a diverse and slow-to-bribe set of governance users, a problem we call swift proportional governance.

The first part of this problem is to select a diverse set of governance users or governors that represent proportionally the voters to prevent an adversary, who controls $f < n/3$ of the $n$ governors, from acting as a dictator. This ratio comes from (i) the need for voters to reach consensus on the new set of governors and (ii) the impossibility of solving consensus with $f \geq n/3$ malicious participants in the general setting [55].

One may think of reconfiguring the governance by executing the byzantine fault tolerant (BFT) consensus protocol of a blockchain not to decide upon a new block but to decide a set of governors [15]. Most blockchain consensus protocols are, however, designed to offer a single-winner election: they are tuned to pick one block out of many legitimate blocks. To make things worse, this picked block in consensus protocols is typically imposed by a winner/leader node [5, 6, 46, 52, 54, 71, 78] that acts as a dictator. For governance, we need instead a multi-winner election protocol so that voters can rank candidates, and the protocol outputs a set of candidates representative of the voted preferences. An example of a multi-winner election protocol is the Single Transferable Vote (STV) protocol [63], used for example to elect the Australian senate [27], that can transfer each vote between candidates in the order of the voter’s preferences. However, this protocol is synchronous and costly [7] to run within a consensus algorithm. Another approach is thus to implement STV in a smart contract: provided that the blockchain is consistent, the output of the smart contract should be the same across users, without the need for an additional consensus step.

The second part of the problem is a fast governance reconfiguration: the longer a proposed governance update takes to be agreed upon, the greater the risk of the governance being bribed. With an average latency of minutes [71] or an hour [52] to commit a transaction agreed by all, blockchains are often subject to congestion when the demand rises [58]. This congestion would also delay the execution of a smart contract intended to update the governance. The recent performance improvements of open blockchains [24, 32, 36, 48] relying on a subset of permissioned service providers to run consensus seems promising for reconfiguration [1, 9, 54, 65]. One of the most recent of these blockchains
Table 1: Blockchains with reconfigurable governance do not offer both proportionality and non-dictatorship

| Blockchain       | Election                      | Proportionality | Non-dictatorship |
|------------------|-------------------------------|-----------------|------------------|
| Tornado          | None                          | no              | no               |
| Algorand         | Sortition                     | no              | no               |
| Hybrid consensus | PoW puzzle                    | no              | no               |
| Zilliqa          | PoW puzzle                    | no              | no               |
| OmniLedger       | Sortition                     | no              | no               |
| RapidChain       | PoW puzzle                    | no              | no               |
| ComChain         | None                          | no              | no               |
| Libra            | None                          | no              | no               |
| SmartChain       | None                          | no              | no               |
| Polkadot         | Multi-winner approval voting  | yes*            | no               |
| EOS              | Multi-winner approval voting  | yes*            | no               |
| SocChain         | Multi-winner preferential voting | yes*         | yes              |

* Polkadot and EOS offer some form of "proportionality" but do not satisfy the traditional definition we use [72].

This paper defines the swift proportional governance problem (§3), designs a solution for it, proves the solution correct and evaluates the solution. Our proposed solution offers two practical contributions: an election decentralized application, or DApp, that elects a set of governors ensuring proportionality and non-dictatorship (§4) and a blockchain (§5) that swiftly replaces a set of governors by this newly elected one. In particular, Table 1 indicates why other blockchain governance protocols do not address the same problem (the detailed comparison is deferred to §7). The problem our election protocol solves NP-hard (§6.2.3) and, as we explain in §6.3, it would be too slow to cope with bribery if executed on another blockchain. More specifically, our contributions are as follows:

- We introduce the first byzantine fault tolerant multi-winner election protocol, called BFT-STV, a new primitive that augments the STV election procedure to enforce non-dictatorship in the presence of at most \( t < n/3 \) byzantine voters among \( n \) voters without assuming synchrony (we denote by \( f \leq t \) the actual number of byzantine voters). We implement this new protocol in a smart contract written in the Solidity programming language to allow the users of a blockchain to propose and rank candidates in the order of their preferences. As it is impossible to distinguish a non-responsive byzantine voter from a delayed message, we introduce a new election quota \( q_B = \frac{t}{k} \) where \( k \) is the size of the committee. Interestingly, we show that our new BFT-STV protocol preserves the proportionality and non-dictatorship properties of STV while ensuring termination.

- This smart contract alone is not sufficient to ensure the swiftness of the governance reconfiguration, especially with Ethereum. Our second contribution is a blockchain, called SocChain (Social Choice Blockchain), that reconfigures itself by taking as an input the elected committee of governors output by the smart contract. Similarly to the "open permissioned" Red Belly Blockchain [24], SocChain accepts permissionless clients to issue transactions that permissioned governors agree upon. The key difference is that SocChain embeds the Ethereum Virtual Machine supporting smart contracts that can modify, at runtime, the set of permissioned nodes governing the protocol. It then reconfigures the blockchain nodes in order to mitigate bribery attacks. In particular, our protocol revokes permissions of existing governors to select new governors before a large portion of them could be bribed. This is done by changing the governor set periodically and rapidly by electing new governors.

- We prove that our protocols are correct and evaluate the time they take to reconfigure a blockchain with up to 150 voters electing governors among 150 candidates. Our results indicate that it always takes less than 5 minutes for SocChain to elect new governors and transition from using the old governors to using the new governors that will produce the upcoming blocks. Finally, we also evaluate SocChain at a larger scale, showing that it performs thousands of transactions per second when deployed on 100 VMs, hence being able to replicate the governance maintained by major global organizations such as OECD, EU, the CommonWealth, APAC, which all have under 100 members.

In the remainder of the paper, we present the background and motivations (§2), and our goal, model, and problem definition (§3). We present our new secure governance DApp (§4) and prove it correct. We then present SocChain (§5), and evaluate it with our new secure governance DApp (§6). Finally, we present the related work (§7) and conclude (§8). We defer the proof of correctness of our blockchain (§A), the discussion of our solution (§B) and the Solidity code of the BFT-STV smart contract (§C) to the optional appendix.

2 BACKGROUND AND MOTIVATIONS

The notion of governance, which is the processes relied on to make decisions impacting the protocol has become an important topic in blockchain [14, 51, 75]. The governance structure encompasses the identity of parties capable of suggesting changes, the avenue through which such changes are proposed, the users capable of deciding the changes and the parties implementing these changes. Due to the large number of users of a blockchain, governance is especially relevant to lead this large cohort towards a common goal. With a lack of governance, the divergence of opinions may result in the split of the blockchain into multiple instances sharing a common transaction history but accepting distinct transactions.

As an example, consider Figure 1, where blockchain node 1 rejects a software upgrade and keeps accepting old-formatted blocks whereas blockchain node 2 accepts this upgrade and starts accepting blocks in a new format, leading to a hard fork. The two largest blockchains were victims of such splits: Bitcoin is now split into
BTC and BCH [68] whereas Ethereum is now split into ETH and ETC [42]. The absence of governance can draw blockchain users into such clashes. The solution to this problem, which we adopt here, is to “hard-code” in the blockchain software a reconfiguration (or upgrade) that executes as soon as it is voted upon. When the blockchain is spawned for the first time, all its users implicitly accept that it may reconfigure. Later, if a majority of voters decide to reconfigure, then the blockchain changes the software and its governance users, automatically. There is no need for the users to decide whether to upgrade as their blockchain node reconfigures autonomously.

The biggest challenge is to prevent an attacker from obtaining the control of the governance, which is usually tackled through decentralization. Recently, the best paper at OSDI 2020 [76] proposes to apply social choice theory results to distributed systems in order to guarantee that no coalition of \( f < n/3 \) governors can dictate the order of transactions. Its authors assume that the governors running the consensus are pre-determined and do not aim at running an election that will update this set of governors. The reason for this assumption stems from the conjunction of two fundamental results of distributed computing indicating that one cannot implement a secure blockchain as soon as the oligarchy includes \( n/3 \) participants because (i) a blockchain needs to solve consensus in the general setting [37] and (ii) consensus cannot be solved if network delays cannot be predicted [34]. As soon as more than \( n/3 \) of the governors fail, then the governance cannot lead participants towards the same goal anymore.

As blockchains typically handle valuable assets, several works already noted the risk for a user to bribe other users to build an oligarchy capable of stealing these assets [12]. As mentioned before, it is reasonable to assume that bribing many nodes is not instantaneous [36, 45, 49, 74]. To reduce the chances that governance users, or governors, know each other, Algorand [36] exploits randomness and non-interactivity [2], however, a random selection does not eradicate the possibility of obtaining a byzantine oligarchy, because in Algorand the more coins users have, the higher their chances of being selected. Other blockchains assume explicitly a *slowly-adaptive adversary* [45, 50], assuming that the adversary can corrupt a limited number of nodes on the fly at the beginning of each consensus epoch but cannot change the set of malicious participants during an epoch. We build upon such an assumption to implement SocChain (§5).

Traditional blockchains do not offer a representative governance [11]. Some blockchains give permissions to miners to decide to change the gas price [58], others give the permission of deciding a new block randomly [36], some prevent governors from changing the governance size [30]. The closest work, concomitant with ours and part of Pokadot [14], targets proportional representation while favoring the wealthiest users by offering an approval voting system. Given the Pareto Principle [53] stating that few users typically own most of the resources, care is needed to avoid falling back to an oligarchy. In order to pursue the two conflicting goals of letting the wealthiest participants govern while trying to avoid that they constitute an oligarchy, Polkadot can only offer some approximation to the problem solution [19]. Instead of approximating a solution that could result in the blockchain being unusable, we offer a preferential voting system that solves exactly the problem of proportional representation and non-dictatorship as we explain in §3.2.

### 2.1 Social choice theory with byzantine fault tolerance

To propose meaningful properties for blockchain governance, we draw inspiration from classic work on social choice theory. Given a set of \( n \) voters, each casting an *ordinal ballot* as a preference order over all \( m \) candidates, a *multi-winner election* protocol outputs a winning committee of size \( k \).

Arrow [3] defined non-dictatorship as a property of a voting protocol where there is no single person that can impose its preferences on all. Our goal is to adapt this property to cope with byzantine voters such that non-dictatorship remains satisfied even when an adversarial person controls up to \( f < n/3 \) byzantine voters (Def 1).

Non-dictatorship is however insufficient to guarantee that newly elected governors remains a diverse representation of the voters. Black [11] was the first to define this proportionality problem where elected members must represent “all shades of political opinion” of a society.

Dummett [25] introduced fully proportional representation to account for ordinal ballots, containing multiple preferences. Given a set of \( n \) voters aiming at electing a committee of \( k \) governors, if there exists \( 0 < \ell \leq k \) and a group of \( \ell \cdot q_H \) all rank the same \( \ell \) candidates on top of their preference orders, then these \( \ell \) candidates should all be elected. However, it builds upon Hare’s quota \( q_H \), which is vulnerable to strategic voting whereby a majority of voters can elect a minority of seats [39]. This problem was solved with the introduction of Droop’s quota \( q_D \) as the smallest quota such that no more candidates can be elected than those seats to fill [63].

Woodall [72] replaces Hare’s quota with Droop’s quota \( q = n q_D \) and defines the *Droop proportionality criterion* as a variant of the fully proportional representation property: if for some whole numbers \( j \) and \( s \) satisfying \( 0 < j \leq s \), more than \( j \cdot q_D \) of voters put the same \( s \) candidates (not necessarily in the same order) as the top candidates in their preference list, then at least \( j \) of those \( s \) candidates should be elected. This is the property we target in this paper and we simply rename it *proportionality* (Def 1).

It is known that the First-Past-The-Post (FPTP) single-winner election and the Single Non-Transferrable Vote (SNTV) multi-winner election cannot ensure fully proportional representation [33]. The reason is that voters can only reveal their highest preference.

This property can however be achieved using the *Single Transferable Vote (STV)* algorithm with Hare’s quota \( q_H = \frac{2}{k} \). In STV,
We consider a distributed system of $n$ voters among which up to $n/2$ are byzantine one. Considering $n$ as the number of governors or potential voters among which up to $t$ can be bribed or byzantine, our protocol can only wait for at most $n - t$ votes to progress without assuming synchrony. Waiting for $n - t$ prevents us from guaranteeing that the aforementioned quotas can be reached. We thus define a new quota called the byzantine quota $q_B = \lceil \frac{n-1}{3} \rceil$ such that $t < n/3$ and reduce the number of needed votes to start the election to $n - t$. Of course, up to $t$ of these $n - t$ ballots may be cast by byzantine nodes, however, we show in Theorem 2 that no adversary controlling up to $t$ byzantine nodes can act as a dictator. Based on $q_B$, we propose BFT-STV that extends STV for a byzantine fault tolerance environment. We also show that BFT-STV satisfies proportionality and non-dictatorship (§4) without assuming synchrony.

3 THE SWIFT PROPORTIONAL GOVERNANCE PROBLEM

Our goal is to offer swift proportional governance by: (i) offering a blockchain governance that allows distributed users to elect a committee proportionally representative of the voters and without dictatorship and (ii) guaranteeing security of the blockchain by changing rapidly its governance. We first present the computation model (§3.1) before defining the BFT governance (§3.2) and blockchain (§3.3) problems separately, and terminate with the threat model (§3.4).

3.1 Byzantine fault tolerant distributed model

We consider a distributed system of $n$ nodes, identified by public keys $I$ and network identifiers (e.g., domain names or static IP addresses) $\Delta$, that can run different services: (i) the state service executes the transactions and maintains a local copy of the state of the blockchain, (ii) the consensus service executes the consensus protocol in order to agree on a unique block to be appended to the chain. Client nodes simply send transaction requests to read from the blockchain (to check an account balance) or to transfer assets, upload a smart contract or invoke a smart contract.

As we target a secure blockchain system running over an open network like the Internet, we consider the strongest fault model called the byzantine model [47], where nodes can fail arbitrarily by, for example, sending erroneous messages and we do not assume that the time it takes to deliver a message is upper bounded by a known delay, instead we assume that this delay is unknown, a property called partial synchrony [26]. We also aim at implementing an optimally resilient system: as blockchain requires consensus in the general model [37] and consensus cannot be solved in the partially synchronous model with $n/3$ byzantine nodes [47], we assume a slowly adaptive byzantine adversary where the number $f$ of byzantine governors can grow up to $t < n/3$ within the first $\Delta$ units of time of the committee existence (we will show in §6 how $\Delta$ can be made as low as 5 minutes). A node that is not byzantine is called correct. Finally, we assume public key cryptography and that the adversary is computationally bounded. Hence, the issuer of a transaction can sign it and any recipient can correctly verify the signature.

3.2 Secure governance problem

We refer to the blockchain governance problem as the problem of designing a BFT voting protocol in which $n$ voters rank $m$ candidates to elect a committee of $k$ governors ($k < m \leq n$) to ensure non-dictatorship as defined by Arrow [3] and proportionality as defined by Dummett [25], Woodland [72] and Elkind et al. [29] (cf. §2.1). The main distinction is that we adapt this problem from social choice theory to the context of distributed computing.

**Definition 1 (The Secure Governance Problem).** The secure governance problem is for a distributed set of $n$ voters, among which $f \leq t < n/3$ are byzantine, to elect a winning committee of $k$ governors among $m$ candidates (i.e., $m > k$) such that the following properties hold:

- **Proportionality:** if, for some whole numbers $j, s$, and $k$ satisfying $0 < j \leq s \leq k$, more than $j(n - 1)/(k + 1)$ of voters put the same $s$ candidates (not necessarily in the same order) as the top $s$ candidates in their preference listings, then at least $j$ of those $s$ candidates should be elected.
- **Non-dictatorship:** a single adversary, controlling up to $f < n/3$ byzantine voters, cannot always impose their individual preference as the election outcome.

The need for these two properties stems from our goal of guaranteeing proportional representation (proportionality) but also disallowing a coalition of byzantine nodes from imposing their decision on the rest of the system (non-dictatorship). Note that the non-dictatorship property differs slightly from the original definition [3] that did not consider a byzantine coalition. In particular, our property considers coalitions and prevents them from imposing their preference in “all” cases.

3.3 Blockchain problem

We refer to the blockchain problem as the problem of ensuring both the safety and liveliness properties that were defined in the literature by Garay et al. [35] and restated more recently by Chan et al. [20], and a classic validity property [24] to avoid trivial solutions to this problem.

**Definition 2 (The Blockchain Problem).** The blockchain problem is to ensure that a distributed set of blockchain nodes maintain a sequence of transaction blocks such that the following properties hold:

- **Liveness:** if a correct blockchain node receives a transaction, then this transaction will eventually be reliably stored in the block sequence of all correct blockchain nodes.
- **Safety:** the two chains of blocks maintained locally by two correct blockchain nodes are either identical or one is a prefix of the other.
• Validity: each block appended to the blockchain of each correct blockchain node is a set of valid transactions (non-conflicting well-formed transactions that are correctly signed by their issuer).

The safety property does not require correct blockchain nodes to share the same copy, simply because one replica may already have received the latest block before another receives it. Note that, as in classic definitions [20, 35], the liveness property does not guarantee that a client transaction is included in the blockchain: if a client sends its transaction request exclusively to byzantine nodes then byzantine nodes may decide to ignore it.

3.4 Threat model
As in previous blockchain work [36, 45, 50, 74], we assume a slowly adaptive adversary with a limited bribing power that cannot, for example, bribe all users instantaneously. More precisely, provided that any new set of governors is elected with proportional representation, we also assume that it takes more than \( \Delta = 5 \) minutes for 1/3 of new governors to misbehave as part of the same coalition. We will show in §6 that \( \Delta = 5 \) minutes is sufficient once the votes are cast as SocChain reconfigures its governance in less than 5 minutes. In comparison, once it will be available, Eth2.0 will take at least 6.4 minutes to reconfigure governance [70].

For the initial set of governors to be sufficiently diverse, we can simply select governors based on their detailed information. This can be done by requesting initial candidates to go through a Know-Your-Customer (KYC) identification process, similar to the personal information requested by the Ethereum proof-of-authority network to physical users before they can run a validator node [56]. A set of governors could then be selected depending on the provided information by making sure multiple governors are not from the same jurisdiction, they are not employed by the same company, they represent various ethnicities, they are of balanced genders, etc. We defer the details of how the KYC process can be implemented, how user anonymity can be preserved and how to cope with bribery smart contract attacks in §B.

3.4.1 Bribery attack. Limiting the number of nodes responsible to offer the blockchain service as done in recent open blockchains [24] exposes the service to a bribery attack [12], which is an act of offering something to corrupt a participant. This is because it is typically easier to bribe fewer participants. In particular, as consensus cannot be solved with at least \( 2/3 \) byzantine processes among \( n \) when message delays are unknown [26], it is sufficient to bribe \( n/2 \) processes to lead correct blockchain nodes to disagree on the next block appended to the blockchain and thus create a fork in the blockchain. The attacker can then exploit this fork to have its transaction discarded by the system and then re-spend the assets he supposedly transferred in what is called a double spending. Our reconfiguration protocol mitigates such a bribery attack in the presence of a slowly-adaptive adversary by re-electing \( n \) new governors that execute the consensus protocol every \( x \) blocks (by default we use \( x = 100 \)). This is how we prevent the risks that \( \frac{2}{3} \) of the current governors get bribed when the blockchain has between \( k \) and \( k + x \) blocks. As \( x \) consecutive block creations do not always translate into the same time interval, we detail in §B how one can make sure that, periodically, exactly \( x \) blocks are created.

3.4.2 Sybil attacks. A Sybil attack consists of impersonating multiple identities to overwhelm the system—in the context of votes, a Sybil attack could result in double voting. The traditional blockchain solution, proof-of-work [52], copes with Sybil attacks by requiring each block to include the proof of a crypto puzzle. Proof-of-stake, give permissions to propose blocks to the wealthiest participants by relying on the assumption that participants with a large stake in the system behave correctly. We adopt a third solution that consists of providing authenticating information, in the form of know-your-customer (KYC) data, in exchange for the permission to propose new blocks, vote for governors, or be a governor candidate. This authentication copes with Sybil attacks by preventing the same authenticated user from using distinct node identities (as detailed in §B).

4 BYZANTINE FAULT TOLERANT PROPORTIONAL GOVERNANCE
In this section, we present how to elect, despite \( f \leq t < n/3 \) byzantine nodes, a diverse set of governors. The idea is to allow a set of \( n \) blockchain nodes that vote to elect a committee proportionally representing the voters. To this end, we propose the Byzantine Fault Tolerant Single Transferrable Vote (BFT-STV) smart contract that implements a multi-winner election that solves the governance problem (Def. 1). We detail how to integrate it into SocChain in §5.

4.1 Overview
In order to guarantee that the election ensures fully proportional representation, we designed the BFT-STV algorithm and implemented it in a smart contract. In this section, we present its high level pseudocode and defer the details of its implementation to §C. To bootstrap, the initial permissions to vote are obtained by \( n \) initial governors after identification (KYC) to ensure diversity and prevent Sybil attacks (§3.4.2). Recall that governors cannot use the classic STV algorithm to elect a new committee as the smart
Algorithm 1: Byzantine Fault Tolerant Single Transferable Vote (BFT-STV) - Part 1

4.2 Byzantine Fault Tolerant Single Transferable Vote

Algorithm 1 presents the main functions of the BFT-STV smart contract that the governors can invoke whereas Algorithm 2 is the classic STV algorithm adapted to progress in a partially synchronous [26] environment and despite the presence of up to \( t \) Byzantine voters, hence its name SVTg.

Initially, the governors cast their ballots by invoking the function cast-ballot(\( b \)) at line 12 of Algorithm 1. As a result, the smart contract verifies that the ballots are well-formed (line 13). This involves checking that the governors have not voted for themselves on their ballots and there are no duplicated preferences. Although the details are deferred to the Appendix 5C for simplicity in the presentation, note that the smart contract keeps track of the public keys of the governors casting ballots to ensure that the same governor cannot double vote. Once the smart contract receives \( n - t \) well-formed ballots the change-committee(\( b \)) function is invoked (line 15). The change-committee function starts by computing the score of the valid candidates as the number of votes they receive at lines 17–18. Valid candidates are initially selected through KYC (§34.2) before being periodically voted upon by governors. A preference pointer is initialized to the first preference of each ballot at line 19. Then a new round of the STV election process starts (lines 20–23). This execution stops once the committee of new governors is elected (line 21). If before the targeted committee is elected, the number of
eliminated candidates has reached a maximum and no more candidates can be eliminated to achieve the target committee size, then the STV election stops (line 24). The remaining non-eliminated candidates are elected by decreasing order of preferences at lines 25–28 until the target committee size is reached. Finally, the smart contract emits the committee of elected candidates (line 29), which notifies the replicas of the election outcome.

4.3 Classic STV with the byzantine quota
Algorithm 2 presents the classic STV algorithm but using the new byzantine quota $q_B$ by electing candidates whose number of votes exceed $q_B$ (line 40). This algorithm executes two subsequent phases: in the first phase (lines 39–56) the algorithm elects the candidates whose number of votes exceeds the quota $q_B = \frac{n - t}{k + 1}$; in the second phase (lines 57–79), the algorithm eliminates the least preferred candidate if no candidates received a number of votes that exceeds the quota. In each round of STV function call (line 22), when a candidate exceeds the quota (line 40), their excess votes are transferred to the next eligible preferences of the ballots that contain the candidate (line 56). In each round of ballot iteration, if no candidate has reached the quota, the candidate with the least vote(s) is eliminated (line 58). This candidates’ excess votes are transferred to the next eligible preference of the ballots that contain the candidate that received the least votes (line 78). The elimination of candidates stops when no more candidates can be eliminated to achieve the committee size (line 24). At this point, even though the remaining candidates did not receive enough votes to reach the quota, they are elected as part of the committee (line 28).

4.4 Proofs of secure governance
In this section, we show that BFT-STV (Algorithms 1 and 2) solves the secure governance problem (Def. 1). To this end, the first theorem shows that the BFT-STV protocol ensures Proportionality. As mentioned in §3.2, recall that $n$, $m$ and $k$ denote the number of voting governors, the number of candidates and the targeted committee size, respectively. As we consider byzantine nodes, note that the proof holds even if malicious voters vote in the worst possible way (e.g., based on what the others have voted).

Theorem 1. The BFT-STV multi-winner election protocol satisfies Proportionality.

Proof. By examination of the code of Algorithms 1 and 2, the only difference between BFT-STV and STV is the number of votes needed to elect a candidate. STV typically starts with $n$ received ballots whereas the BFT-STV starts the election as soon as $(n - t)$ ballots are received (line 14 of Alg. 1), where $t$ is the upper bound on the number $f$ of byzantine nodes and $n$ is the total number of governors eligible to vote. This number of BFT-STV ballots is distributed among a larger number of candidates. This can result in less than $k$ candidates receiving enough votes to reach the classic STV quota where $k$ is the size of the committee. By the Proportionality definition (Def. 3.2), we need to show that if $j \cdot (n - t)/(k + 1)$ voters put the same $s$ candidates as the top $s$ candidates in their ballot preference, then those $s$ candidates will still be elected. The proof follows from [41, p. 48–49]: line 58 of Algorithm 2 indicates that by elimination, the votes will still be concentrated on the top $j$ candidates such that $0 < j \leq s$. As a result, $j$ of those $s$ candidates will still be elected satisfying Proportionality. □

The next theorem shows that the BFT-STV protocol ensures Non-dictatorship as defined in Definition 1.

Theorem 2. The BFT-STV multi-winner election protocol satisfies Non-dictatorship.

Proof. The proof shows the existence of an input of correct nodes for which a single adversary controlling $f$ byzantine nodes cannot have its preference $b_a$ be the winning committee. Let $b_a[-1]$ be the least preferred candidate of the adversary, we show that there exist preferences $b_1, ..., b_{n-f}$ from correct nodes such that the winning committee includes $b_a[-1]$. The result then follows from the assumption $k < m$.

By examination of the pseudocode, the winning committee is created only after receiving $n - t$ correctly formatted ballots (line 13 of Alg. 1). By assumption, there can only be at most $f \leq t < n/3$ ballots cast by byzantine nodes. As a result, among all the $n - t$ received ballots, there are at least $n - 2t > n/3$ ballots cast from correct nodes. In any execution, an adversary controlling all the byzantine nodes could have cast at most $f$ ballots as the adversary cannot control the ballot cast by correct nodes. Let $b_1, ..., b_{n-f}$ be the ballots input by correct nodes to the protocol such that their first preference is the least preferred candidate of the adversary, i.e., $\forall i \in \{1, n - t\}: b_i = b_a[-1]$. Because $f \leq t < n/3$, we know that $b_a[-1]$ will gain more votes than any of the other candidates, and will thus be the first to be elected (line 40 of Alg. 2). By assumption, we have $k < m$, which means that there is a candidate the adversary prefers over $b_a[-1]$ that will not be part of the winning committee. Hence, this shows the existence of an execution where despite having an adversary controlling $f$ byzantine nodes, the adversary preference is not the winning committee. □

5 SOCHAIN: ENABLING BLOCKCHAIN

In this section, we present the blockchain called SocChain and how it provides the swift governance reconfiguration based on our BFT-STV smart contract (§4). We show that SocChain solves the Blockchain problem (Def. 2) in §3.3. The design of SocChain is inspired by the open permissioned Red Belly Blockchain [24]; while any client can issue transactions without permission, a dynamic set of permissioned consensus participants decide upon each block. As a result, SocChain ensures instant finality (by not forking), and is optimally resilient in that it tolerates any number $f \leq t < n/3$ of byzantine (or corrupted) nodes. However, SocChain differs from the Red Belly Blockchain by mitigating bribery attacks and by integrating the Ethereum Virtual Machine (EVM) [71] to support smart contracts necessary to offer the swift proportional reconfiguration.

5.1 Reconfigurable governance with the BFT-STV smart contract
We now present how the blockchain is reconfigured with the new consensus committee once the BFT-STV smart contract elects the committee. Offering proportional representation and non-dictatorship is not sufficient to cope with an adaptive adversary.
In order to mitigate bribery attacks, we now propose a swift reconfiguration that complements the BFT-STV algorithm. Provided that you have $n$ nodes, it is sufficient to have $n/3$ corrupted nodes among them to make the consensus service inconsistent. This is because consensus cannot be solved with $n/3$ byzantine nodes [47]. In particular, it is well-known that neither safety (agreement) nor liveness (termination) of the consensus can no longer be guaranteed as soon as the number of failures reaches $n/3$ [22]. As a result, a coalition of $n/3$ byzantine nodes can lead the set of nodes to a disagreement about the next block to be appended to the chain. An attacker can leverage these conflicting blocks in order to double spend: for example if it has two conflicting transactions in those blocks.

5.1.1 How to ensure the existence of candidates. In order to bootstrap, an initial set of candidate nodes willing to provide the blockchain service and voter nodes is provided as part of the blockchain instance. Upon each block creation and as in classic blockchain solutions [52, 71], SocChain offers a reward to each voter. We assume that this reward incentivizes sufficiently many nodes to be candidates at all times. There are few restrictions that need to be enforced in order to guarantee that the elected committee will proportionally represent voter nodes. First, the voters and the candidates set has to be large enough to represent all groups to which blockchain users belong. Second, the voters should not try to elect themselves—this is why we restrict the set of candidates to be disjoint from the set of voters, as we explained in §4.2, Fig. 2 and as in other blockchains [14, 31]. These candidates and voters are typically encoded in the blockchain when the blockchain instance is launched, either by hardcoding their public key and network identifier (e.g., domain name or static IP addresses) in the genesis block or by invoking a default smart contract function at start time that records this information. The voters then participate in the election: they cast their ballot by calling another function of the smart contract and passing it a list of candidates ranked in the order of their preferences. A ballot contains the network information of candidates in the order that the voter prefers. (We will present an implementation using static IP addresses in §6.)

Algorithm 3: Reconfiguration of consensus service at a blockchain node

5.1.2 Reconfiguration. In this section, we present the reconfiguration (Algorithm 3) of the blockchain that allows switching from the current committee to the new committee $S$ elected with the BFT-STV (§4) smart contract. Once the network identifiers (domain names or static IP addresses) of the newly selected committee $S$ of governors is emitted by the BFT-STV protocol (line 29 of Algorithm 1), the blockchain nodes are notified with a smart contract event (line 1 of Algorithm 3). The reception of this smart contract event triggers the stopping of the consensus service in the blockchain node through a web3js code (line 2 of Algorithm 3). After the consensus service is stopped, the elected consensus services are reconfigured with the network identifiers of the newly elected nodes (line 6 of Algorithm 3). Finally, the blockchain consensus service is restarted (line 7 of Algorithm 3) to take this new committee into account.

5.2 The transaction lifecycle

In the following, we use the term transaction to indistinguishably refer to a simple asset transfer, the upload of a smart contract or the invocation of a smart contract function. We consider a single instance of SocChain whose genesis block is denoted by $B_0$ and whose blockchain nodes offer a consensus service depicted in Algorithm 5 and a state service depicted in Algorithm 6. Although SocChain also includes smart contracts, its transaction lifecycle is similar to [24] and goes through these subsequent stages:

1. Reception. The client creates a properly signed transaction and sends it to at least one SocChain node. Once a request containing the signed transaction is received (line 1 of Algorithm 4) by the JSON RPC server of our blockchain node running within SocChain, the validation starts (line 2 of Algorithm 4). If the validation fails, the transaction is discarded. If the validation is successful, the transaction is added to the mempool (line 3 of Algorithm 4).

| 1: receive(write, tx) | $\triangleright$ State node upon receiving a transaction |
| 2: if is-valid then | $\triangleright$ if tx is validated |
| 3: mempool $\leftarrow$ mempool $\cup$ \{tx\} | $\triangleright$ add it to mempool |
| 4: wait until \[mempool \rightarrow \text{threshold or timer expired} \] | $\triangleright$ wait sufficiently |
| 5: for each tx in mempool do | $\triangleright$ create proposal |
| 6: prop.txs $\leftarrow$ mempool $\cup$ \{tx\} | $\triangleright$ create proposal |
| 7: mempool $\leftarrow$ mempool \{tx\} | $\triangleright$ remove tx from mempool |
| 8: prop.timestamp $\leftarrow$ timestamp | $\triangleright$ add timestamp to proposal |
| 9: superblock $\leftarrow$ propose(prop) | $\triangleright$ propose to consensus, return superblock |
| 10: exec(superblock) | $\triangleright$ execute superblock |

Algorithm 4: Selection of new transactions to decide

If the number of transactions in the mempool reaches a threshold of transactions or a timer has expired (line 4 of Algorithm 4), then the blockchain node creates a proposal of transactions with the transactions in the mempool (line 6 of Algorithm 4). Consequently, a timestamp is added to the proposal (line 8 of Algorithm 4) and proposed to the consensus service (line 9 of Algorithm 4).

2. Consensus. As in the Democratic Byzantine Fault Tolerant (DBFT) [23], upon reception of the proposal, the blockchain node reliably broadcasts the proposal to other blockchain nodes (line 12 of Algorithm 5) in the same consensus instance. Lines 13–17 of Algorithm 5 present the section of our consensus algorithm. We point the reader to [24] for a detailed description of the consensus protocol and to [8] for the formal verification of its binary consensus. In short, the consensus protocol waits until all proposals have been received for binary consensus instances that have decided (line 18 of Algorithm 5) and forms a superblock out of those proposals (line 19 of Algorithm 5). Finally, the consensus...
service delivers the superblock to the state service (line 9 of Algorithm 4).

Algorithm 5: Consensus protocol

3. Commit. Once the superblock is received by the blockchain node (Algorithm 4, line 9) the commit phase starts. Firstly, each proposal is taken in-order from the superblock and each transaction in it is validated, i.e., its nonce and signature are checked as correct [71] (Algorithm 6, line 25). If a transaction is invalid it is discarded. If a transaction is valid, the transaction is executed and the EVM state trie is updated (Alg. 6, line 26). The execution of a transaction returns the updated state trie \( S_{next} \) and a transaction receipt (Alg. 6, line 26). All the executed transactions in a proposal are written to the transaction trie (Alg. 6, line 30) and all the receipts are written to the transaction receipt trie (Alg. 6, line 31). A block is constructed (Alg. 6, line 33) with hashes returned by the \( h \) function, the gas used \( GU \) by all transactions and the gas limit \( GL \) that can be consumed during the block execution (Alg. 6, line 32), as in Ethereum [71]. Finally the block is appended (Alg. 6, line 34) to the blockchain of the blockchain node.

Algorithm 6: Execution of a superblock by a blockchain node

5.3 A BFT consensus for non-dictatorship

As SocChain builds upon DBFT [23] it is inherently democratic. In fact, DBFT is leaderless which favors non-dictatorship as we explain below: as indicated in Algorithm 5, DBFT reduces the problem of multi-value consensus (to decide upon arbitrary values) to the problem of binary consensus (to decide upon binary values exclusively) by executing an all-to-all reliable broadcast algorithms (line 12) followed by up to \( n \) binary consensus instances (lines 15 and 17) running in parallel. As one can see, in Algorithm 5 all nodes execute the same code and none plays the role of a leader.

By contrast, classic BFT algorithms [10, 13, 17, 38, 40, 73] used in blockchains are generally leader-based. They proceed as follows: A special node among \( n \), called the leader, sends its block to the rest of the system for other nodes to agree that this block is the unique decision. If the leader is slow, then another leader is elected but eventually the block of some leader is decided by all. The drawback with such solutions is that the leader can be byzantine and thus propose the block with the content it chooses. This limitation of leader-based consensus algorithms is precisely the motivation for a recent work [76] that aims at circumventing byzantine oligarchy by ensuring that if non-concurrent transactions are perceived in some order by all correct nodes, then they cannot be committed in a different order.

To place this problem in our context, consider Figure 3 depicting an execution of BFT-STV (Algorithm 1) in one of these leader-based blockchains with \( n = 7 \) and \( f = 2 \). (Recall that without assuming synchrony, the smart contract cannot wait for \( n \) transactions from distinct processes as it cannot distinguish between a slow process and a Byzantine process that do not send its invocation. As a result the smart contract can only wait for at most \( n - t \) invocations before continuing its execution to avoid blocking forever.) Consider that in this particular execution, the \( n - t \) correct nodes issue a transaction (Fig. 3(a)) invoking the function cast-ballot with their candidate preferences before any Byzantine node issued any transaction invoking cast-ballot (Fig. 3(b)). These transactions are not yet committed and are still pending, when the leader creates its block by including the transactions it has received. If the leader is Byzantine, it may wait and gather transactions issued by all the Byzantine nodes of its coalition before creating its proposed block. Once it receives \( t \) transactions from Byzantine nodes it then creates its block with its transactions issued from Byzantine nodes and \( n - 2t \) transactions issued by correct nodes (Fig. 3(c)), before proposing it to the consensus. Once this block is decided, the transactions it contains that invoke cast-ballot are executed. As a result, the BFT-STV smart contract finally returns a committee voted upon by \( t \) Byzantine nodes and \( n - 2t \) correct nodes, whereas without the leader the BFT-STV smart contract could have returned a committee voted upon by \( n - t \) correct nodes.
SocChain is immune to this dictatorship problem without assuming synchrony due to its democratic consensus algorithm [23]. More precisely, Algorithm 5 does not decide a single block proposed by any particular node or leader. Instead it decides the combination of the blocks proposed by all consensus participants, hence called superblock (line 19) as in [24]. All nodes reliably broadcast its block and participate in a $k^{th}$ binary consensus by inputting value 1 if it received the proposal from the $k^{th}$ node. If no block is received from the $k^{th}$ node, then the $k^{th}$ binary consensus is invoked with input value 0. The outcome of these $n$ binary consensus instances are stored in a bitmask (lines 15 and 17). Finally the bitmask is applied to the array of received blocks to extract all transactions that will be included in the superblock (line 19). Hence the inclusion of a particular block is independent of the will of a single node, that could otherwise act as a dictator.

6 EVALUATION OF SOCCHAIN

In this section, we evaluate the performance of SocChain on up to 100 machines located in 10 countries. We measure the performance of reconfiguring the blockchain nodes in SocChain in terms of the time taken to stop the blockchain service with the previous committee and re-start the blockchain service but with a new committee. We also evaluate the execution time of the BFT-STV smart contract depending on the number of candidates and voters. Finally, we show that a growing number of blockchain participants marginally impacts SocChain’s performance.

6.1 Experimental settings

We now present the experimental settings of our evaluations dedicated to test the performance.

6.1.1 Controlled setting. In order to evaluate SocChain, we deployed SocChain on up to 100 VMs. In order to combine realistic results and some where we could control the network, we deployed VMs on Amazon Web Services (AWS) and an OpenStack cluster where we control the delay using the tc command. We also measured world-wide delays using 10 availability zones of AWS located across different countries. On AWS, we deployed up to 100 VM instances with 8 vCPUs and 16 GB of memory connected through Internet. On OpenStack we deployed up to 20 VM instances with 8 vCPUs and 16 GB of memory connected through a 10 Gbps network where we added artificial network delays under our control to represent the latencies observed over the Internet across different geographical regions.

6.1.2 Client setup. In our experiments, we send a fixed number of transactions from each client machine to keep the sending rate constant. Each client instance sends a distinct set of transactions to a specific blockchain node. The sending is done concurrently to each blockchain node so as to stress-test the blockchain.

6.2 Reconfiguration performance

In this section we demonstrate that SocChain fully reconfigures its governance with world-wide candidates in less than 5 minutes while ensuring proportional representation of its voters. More specifically, we evaluate the time it takes to completely reconfigure the blockchain by replacing a committee of blockchain nodes by another (cf. Algorithm 3). To this end, we capture the time it takes to execute the BFT-STV smart contract (i.e., the execution time of BFT-STV) and start all the newly elected blockchain nodes after initiating a stop on the previous blockchain committee (i.e., the restart time). We define this time as the reconfiguration time (i.e., reconfiguration time = execution time of BFT-STV + restart time).

6.2.1 Realistic network delays. In order to mimic realistic Internet delays in our controlled setting, we deployed 20 VMs on OpenStack with 2 VMs per blockchain node, each dedicated for the state service and the consensus service (§5.2). We added communication delays between the blockchain nodes taken from the AWS geo-distributed environment latencies that we measured separately. Note that this is to evaluate the restart time of blockchain nodes in a geo-distributed setting.

6.2.2 Restart time. Figure 4 presents the restart time in seconds when a committee of varying size gets started from a total of 10 consensus blockchain nodes. In particular, we evaluate the restart time when it changes the targeted committee size starting from 10 and targeting a size ranging between 4 and 7 in order to observe whether this size affects the reconfiguration time. Note that the lower the time the more available the blockchain is because this time can translate into system outage during which the newly requested transactions may not be serviced—without violating liveness [20, 35] (Def. 2). We observe that the restart time varies by 5% depending on the targeted committee size but that the maximum time is taken when targeting a committee size of 8 nodes, while the minimum time is taken when targeting a committee size of 7 nodes. This indicates that the restart time is not impacted by the selected targeted committee sizes. To assess the impact of large committee sizes, we experiment below with a larger committee, with 150 voters ranking 150 candidates.

6.2.3 Impact of the complexity on reconfiguration. Unlike Ethereum or Bitcoin, SocChain does not unnecessarily incentivize thousands of participants to execute the same task, hence SocChain can restrict the committee size. It is well-known that voters of the STV algorithm have to execute an NP-hard computation, so the same applies to the BFT-STV problem. By contrast with concomitant proposals [19] that approximate other NP-hard proportional election problems, our solution achieves proportionality exactly (Theorem 1). Without approximating the solution, our exact solution

| Target committee size | Restart time (sec) |
|-----------------------|--------------------|
| 4                     | 10                 |
| 5                     | 20                 |
| 6                     | 30                 |
| 7                     | 40                 |
| 8                     | 50                 |
| 9                     | 60                 |

Figure 4: Restart times in seconds when changing the consensus committee from 10 to target size $k$. Blockchain liveness remains guaranteed despite reconfiguration as either the correct blockchain node does not receive the transaction due to transient outages or commits it eventually.
could induce a cost growing super-linearly with the input size (e.g., number of voters and candidates) of the problem. To measure the impact of these parameters, we varied the number \( n \) of voters and the number \( m \) of candidates from 50 to 150 while executing BFT-STV to reduce the committee of \( m/2 \) governors. Recall that \( m \leq n \) (§3.2), so while we fixed \( m = 50 \) while varying \( n \), we had to fix \( n = 150 \) to vary \( m \) up to 150.

Figure 5 depicts the median execution times of BFT-STV and its errors bars (as minima and maxima) over 3 runs for each different pair of numbers \( n \) and \( m \) of voters and candidates, respectively. To this end, for each of these three runs, we generated a random ordinal ballot for each voter. More precisely, the top curve varies the number \( m \) of candidates whereas the bottom curve varies the number \( n \) of voters.

1. First, we observe that the number of candidates impacts significantly the performance with \( n = 150 \) voters, which confirms our expectation. However, we also observe that the raise decreases as \( m \) exceeds 100. We conjecture that this is due to the way the Ethereum Virtual Machine [71] garbage collects and alternates between CPU resource usage for transaction execution and I/O usage to persist the information when the transaction increases.

2. Second, we observe that when the number of voters increases with \( m = 50 \) the execution time increases sub-linearly: it doubles while the number of voters triples. This is because increasing the number \( n \) of voters helps candidates reach the quota \( q_B \) of votes rapidly without transferring the vote excess. Hence the committee is elected faster than expected and raises only slightly the execution time (despite the extra loop iterations due to the increased number of voters). Overall, electing a committee of 75 blockchain nodes in under 4 minutes due to the increased number of nodes. This is due to the network overhead in the consensus caused by the increasing number of nodes: 99% of the transactions are committed within 37 seconds for 100 nodes. These results can be attributed to the superblock optimization of SocChain.

Note that this is remarkably short compared to the 3-minute expected time taken to execute a single transaction in Ethereum (the Ethereum congestion can make the transaction execution time much longer [58]). While it was expected that the execution of the BFT-STV would take longer as we increase the number of candidates and voters (just like the complexity of STV increases with the problem input size), it was unclear whether SocChain can scale with the number of machines running the blockchain. To this end, in the next section (§6.3), we evaluate the scalability as the impact of the number of VMs participating in the blockchain protocol on its performance.

### 6.3 Large-scale evaluation

In order to better assess the performance at large-scale, we measure the throughput and latencies when running 100 nodes. For this experiment we used native payment transactions of 107 bytes (we evaluate SocChain later with our BFT-STV DApp).

Figure 6 depicts the throughput of SocChain with 20 to 100 blockchain nodes in the AWS Sydney availability zone. Each point is the average over 3 runs and clients send 1500 transactions to each of the SEVM nodes, each client sending at a rate of 4500 TPS.

We observe that the throughput remains above 2000 TPS up to 100 nodes and does not change significantly. We conclude that SocChain performs well in a network of up to 100 nodes. These results can be attributed to the superblock optimization of SocChain.

The 50\(^{th}\), 90\(^{th}\) and 99\(^{th}\) percentiles show a steady rise as expected with the increasing number of nodes. This is due to the network overhead in the consensus caused by the increasing number of nodes: 99% of the transactions are committed within 37 seconds for 100 nodes. These latencies are remarkably low compared to what Ethereum already experienced: 22 seconds for the 50\(^{th}\) percentile of inclusion time, 2 minutes 39 seconds for the 90\(^{th}\) percentile of inclusion time and 47 minutes 34 seconds for the 99\(^{th}\) percentile of inclusion time [58]. In addition, an inclusion does not guarantee a commit in Ethereum as a transaction can be included in an uncle block and be discarded and re-included up to 2 more times [69] later. By contrast, the time to commit in SocChain remains low because SocChain solves consensus deterministically before appending a new block, hence an inclusion is a commit and its user does not have to wait for consecutive appended blocks.
7 RELATED WORK

In this section, we present the work related to governance for blockchains. Table 1, provides a summary of the existing blockchains with reconfigurable governance. For the sake of brevity, we omit in the discussion below the blockchains that assume synchrony [1, 4, 45, 52, 57, 71, 74] or the ones that were shown vulnerable in the absence of synchrony, including blockchains based on proof-of-authority [28].

7.1 Proof-of-stake blockchain governance

Algorand [36] was probably the first blockchain assuming that bribery was not instantaneous like we do (§3.4). Algorand offers governance through sortition, the act of electing governors randomly among a set of candidates. This technique is similar to the jury selection in trials. More precisely, each Algorand node returns a hash h and a proof π by passing a publicly known pseudo random input string to a verifiable random function locally signed. This hash h helps select a node at random depending on the amount of assets the corresponding user has at stake. The selected node can act as a governor and participate in the consensus by piggy-backing the sortition proof π. To mitigate bribery attacks, Algorand replaces governors at each step of the BFT consensus protocol within a consensus round. The key advantage of the sortition is that it is a non-interactive cryptographic technique that prevents the adversary from predicting the future governors. However, Algorand does not aim at offering any proportional representation.

Polkadot [18] rotates its governors every era, a period that lasts about one day, with a multi-winner election. Similarly, our BFT-STV is a multi-winner election (§4) but can replace governors every five minutes (§6). Another difference is that Polkadot exploits a nominated proof-of-stake (NPOS): nominator nodes cast ballots with their preferred candidates based on various parameters (e.g., security practices, staking levels and past performance). The nominators are rewarded with a fraction of the governors gain upon block creations. The key of NPOS is that the more stake a candidate has, the more chance it has to be preferred by a candidate and to eventually become a governor. A nice advantage over Algorand is that Polkadot’s election offers proportional justified representation that limits under-representation. To avoid overrepresentation and to make it expensive for an adversary to impose its candidates in the election, Polkadot approximates a maximin objective, but fails at protecting against dictatorship.

EOS [31] runs a delegated multi-winner approval voting system to elect 21 governors while ensuring some form of proportionality. As opposed to our BFT-STV (§4), approval voting does not allow a voter to indicate its preference between its preferred candidates. As a result EOS cannot solve our secure governance problem (Def.3.2). EOS exploits delegated proof-of-stake (DPOS) where token holders elect governors by casting a vote whose weight is proportional to what the tokens holders have at stake. The elected governors run the consensus and as long as voters who own 2/3 of the stake vote for a block proposed by governors, this block is appended to the chain. EOS may fork in which case the longest chain is adopted as the main one. By contrast, SocChain never forks to avoid risky situations where conflicting transactions in different branches lead to double spending.

The aforementioned solutions weight each vote based on the wealth or assets the corresponding voter owns: the more they own the higher weight their vote gets. Given the Pareto Principle [53] stating that few users typically own most of the resources (as an example in 2021, the wealthiest 1% of US citizens owned about 1/3 of the total wealth⁴), these approaches are vulnerable as soon as one manages to bribe the few wealthiest of all nodes as they likely control a large part of the total stake.

7.2 Proof-of-work blockchain governance

Zilliqa [78] is a sharded blockchain that supports smart contracts and reaches consensus using an efficient version of the leader-based consensus protocol PBFT [17] based on EC-Schnorr multisignature [44, 59]. To shard the network and to reach consensus on transactions, a committee of directory service (DS) nodes is elected with a proof-of-work (PoW) puzzle. Once a candidate node finds the nonce for the PoW, it generates a DS header and multicasts a DS block to the current DS committee. Once the current DS committee reaches consensus on the DS block mined and multicast by the candidate node, the new candidate node is added to the DS committee and the oldest member of the DS committee is removed. The protocol thus ensures that the latest n nodes that have mined a DS block are governors.

The hybrid consensus [54] is a theoretical consensus algorithm for blockchain that selects the most recent ℓ block miners as governors. Similar to Zilliqa, each governor is replaced one at a time following a leader-based consensus algorithm. Unfortunately, we are not aware of any implementation of the hybrid consensus.

Both approaches need as many leader-based consensus executions as there are governors to completely rotate them. By contrast, SocChain rotates them all in a single consensus instance to mitigate the risks of an adversary bribing progressively most of the current governors.

7.3 BFT blockchain governance

The vast majority of byzantine fault tolerant (BFT) blockchains assume that the list of governors is selected by an external service. ComChain [65] lists the public keys of governors in configuration blocks but assumes that the new lists of governors are proposed by an external service. Similarly, Tendermint/Cosmos [62] lists the public keys of governors in blocks but associates a voting power to each validator based on its stake, hence risking the same bribery attacks as other proof-of-stake blockchains (§7.1). SmartChain [9] also stores the committee public keys in dedicated reconfiguration blocks but simply grants governor credentials to every requesting node, without requesting to go through an election. Libra [6] mentions a similar reconfiguration service but no details are provided regarding the selection of governors. As far as we know other BFT blockchains have a static set of consensus nodes, which makes them more vulnerable to bribery attacks, including Stella [48], SBFT [38], Concord [66] and Quorum [21].

⁴https://www.cnbc.com/2021/10/18/the-wealthiest-10percent-of-americans-own-a-record-8percent-of-all-us-stocks.html
8 CONCLUSION

We presented SocChain, a blockchain that solves the swift proportional governance problem by electing a governance committee that is proportionally representative of the voters and by reconfiguring itself fast with this new governance. Its novelty lies in tolerating \( f < n/3 \) Byzantine governors, preventing the adversary from acting as a dictator and reconfiguring sufficiently fast to cope with bribery attacks. Our evaluation shows that SocChain is practical and performs efficiently at 100 nodes. This research bridges the gap between computational social choice and blockchain governance and opens up new research directions related to bribery mitigation and non-dictatorship.

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In this section, we show that SocChain solves the blockchain problem (Def. 2). For the sake of simplicity in the proofs, we assume that there are no malicious nodes playing the roles of consensus nodes and state nodes and are collocated on the same physical machine.

**Lemma 1.** If at least one correct node proposes to a consensus instance $i$, then every correct node decides on the same superblock at consensus instance $i$.

**Proof.** The propose() function is the same as in the Red Belly Blockchain [24] except that we do not use the verifiable reliable broadcast and reconciliation which ensure SBC-validity. Instead we use reliable broadcast and no reconciliation. As such, following from the proof of [24], our blockchain nodes ensure SBC-termination that states that every correct node eventually decides on a set of transactions and SBC-agreement that states no two correct nodes decide on different sets of transactions. Since SocChain consensus returns a superblock (which is a set of transactions) at each instance of consensus $i$, we can say every correct blockchain node decides on the same superblock at consensus instance $i$. □

**Lemma 2.** Variables $TX_k, R_k, S_{next_k}, timestamp_k$ and $val_k$ become identical after executing line 31 of iteration $k$ for any two correct blockchain nodes $P_1$ and $P_2$.

**Proof.** From Lemma 1, every correct consensus node decides on the same superblock at consensus instance $i$. As a result, each correct blockchain node receives the same superblock from consensus instance $i$ (Algorithm 6, line 21). Therefore, each $props[i]$ for any integer $k \in \{0; n\}$ becomes identical at any two correct blockchain nodes $P_1$ and $P_2$ (Algorithm 6, line 23) for consensus instance $i$. As a result, $TX_k, R_k, S_{next_k}, timestamp_k$ and $val_k$ also become identical at $k$ for $P_1$ and $P_2$ for consensus instance $i$ (Algorithm 6, lines 30–33). □

**Lemma 3.** At each index $t$ of the chain, all correct blockchain nodes can only append the same block $B_t$.

For the next lemma we refer to $B_0$ as the genesis block of SocChain.

**Proof.** The proof is by induction on the blocks of the chain.

- **Base case:** if $t = 1$, then $h(H(B_0)) \in B_1$. Since $h(H(B_0))$ is the hash of the header of the genesis block, it is the same for all correct nodes of SocChain. We know from Lemma 2 that variables $h(S_{next_k}), h(TX_k), h(R_k), val_k$ and $timestamp_k$ are identical after line 31 onwards for any two correct blockchain nodes $P_1$ and $P_2$. Therefore, $B_1$ is identical for all correct blockchain nodes.
• **Inductive case**: Let us assume that $B_{\ell-1}$ is identical for all correct blockchain nodes, we show that $B_{\ell}$ is identical for all correct blockchain nodes. Since $B_{\ell-1}$ is identical, $h(H(B_{\ell-1}))$ is identical for all correct blockchain nodes. Using the argument used in the base case, any variable $h(S_{\text{next}_k}), h(T_{\text{X}_k}), h(R_k), v_{\text{al}k}$ and $t_{\text{timestamp}_k}$ are identical after line 31 onwards for any two correct blockchain nodes $P_1$ and $P_2$. Since $B_{\ell} \leftarrow h(H(B_{\ell-1})), h(S_{\text{next}_k}), h(T_{\text{X}_k}), h(R_k), G_{\text{U}k}, G_{\text{L}k}, nonce, t_{\text{timestamp}_k}, v_{\text{al}k}$, it must also become identical for all blockchain nodes after line 31 onwards. Therefore, by induction on each index $\ell$, $B_{\ell}$ becomes identical for all correct blockchain nodes when $B_{\ell}$ is constructed at line 33.

The next three theorems show that SocChain satisfies each of the three properties of the blockchain problem (Definition 2).

**Theorem 3.** SocChain satisfies the safety property.

**Proof.** The proof follows from the fact that any block $B_\ell$ at index $\ell$ of the chain is identical for all correct blockchain nodes due to Lemma 3.

Due to network asynchrony, it could be that a correct node $P_1$ is aware of block $B_{\ell+1}$ at index $\ell + 1$, whereas another correct node $P_2$ has not created this block $B_{\ell+1}$ yet. At this time, $P_2$ maintains a chain of blocks that is a prefix of the chain maintained by $P_1$. And more generally, the two chains of blocks maintained locally by two correct blockchain nodes are either identical or one is a prefix of the other.

**Theorem 4.** SocChain satisfies the validity property.

**Proof.** From Algorithm 6, line 25, only valid transactions are executed and added only such valid transactions are added to block $B_{\ell}$ (Algorithm 6 - lines 28 and 33). Therefore, $\forall$ indexes $\ell$, $B_{\ell}$ is valid $\forall$ correct blockchain nodes.

**Theorem 5.** SocChain satisfies the liveness property.

**Proof.** As long as a correct replica receives a transaction, we know that the transaction is eventually proposed by line 4 of Algorithm 4. The proof follows from the termination of the consensus algorithm and the fact that SocChain keeps spawning new consensus instance as long as correct replicas have pending transactions. The consensus algorithm is DBFT [23] and was shown terminating with parameterized model checking [8].

## B DISCUSSION

Although SocChain offers the swift governance reconfiguration by solving the secure governance problem (Def. 1) and the blockchain problem (Def. 2), there are few secondary aspects that need to be detailed or addressed. Below, we discuss these aspects and propose different extensions to SocChain.

**Know-your-customer (KYC) initial selection.** In SocChain, we employ a know-your-customer (KYC) process when deploying SocChain for the first time in order to assign candidate and voter permissions to blockchain nodes. Similar to VeChain [64] or the EOS-based Voice social network\textsuperscript{5}, we require potential voters and candidates to provide personal information to a decentralized foundation before they can be granted the desired permissions. This personal information can include the name of the user, their biometric details and their preferred role and can be traded against a permission to act as a candidate for election or a voter. The foundation then verifies each user personal information and, when the verification is successful, assigns the specified role to the corresponding user and a one-time secret sent through a secure channel to join SocChain. In SocChain, each voter node is given equal opportunity to elect a candidate to the committee of blockchain nodes. This KYC-based solution thus copes with the risks of building an oligarchy of wealthiest users through proof-of-stake (PoS) or of most powerful machines through proof-of-work (PoW). Although this KYC-based solution requires an offchain verification that is external to the blockchain, note that it is only needed at bootstrap time: any blockchain node deciding to run the code of SocChain (including the BFT-STV smart contract codes) necessarily accepts that the set of voters can automatically elect new candidates and new voters every $x$ blocks without the control of any external company, jurisdiction or foundation.

A possible attack is to upload a bribing smart contract that rewards voters if a specific set of candidates is elected. We underscore that this cannot happen in-band, since such a malicious smart contract needs to be deployed for such a process to take place, and since we assume less than $1/3$ of nodes are Byzantine at all times, such deployments are impossible as a majority would not agree when reaching consensus.

**Domain Name Service (DNS).** For the sake of simplicity in the design of our solution, we implicitly assumed that the IP addresses were static so that nodes would simply need to subscribe to the BFT-STV smart contract to receive an emit event informing them of a list of IP addresses (Algorithm 1 line 29) and allowing them to reconnect to the blockchain nodes running the consensus service. Although this assumption is suitable when experimenting on a controlled set of VMs provided by a cloud provider, the IP addresses of Internet users are often dynamically assigned, which makes our solution unrealistic. One can easily adapt the current implementation to support domain names instead of IP addresses. While this solution requires a Domain Name Service (DNS) that, if centralized, could defeat the purpose of the blockchain, note that the hard-coded DNS server addresses are already used by classic blockchains for node discovery [52]. SocChain can exploit DNS in a similar fashion but to offer governance reconfiguration by updating promptly the DNS so as to redirect all clients to the new committee and to mitigate long-range attacks.

**Gas cost of reconfiguration execution.** As SocChain builds upon the Ethereum Virtual Machine (EVM) [71], it inherits the notion of gas that avoids the infinite execution of smart contracts. The gas is a unit that reflects the work required for a particular sequence of execution steps in Ethereum [71]. The more computation is required to execute a transaction, the more gas this transaction requires to complete. It is the client’s role to pay each unit of gas that is consumed by the transaction it issued in the blockchain. The price of this gas unit is known as the gas price and is considered as the transaction fee to reward the blockchain node (called ‘miner’ in Ethereum) who mined the block containing the transaction. In

\textsuperscript{5}https://crypto-economy.com/ eos-based-social-network-voice-announces-human-sign-up-an-alternative-for-kyc/
the BFT-STV smart contract, the election execution cost between 340029258 and 2347870086 gas units. The gas price depends on the network traffic and if a client requires to have their transactions treated as priority by miners, then they should include a high gas price. However, if we use a high gas price, the transaction cost becomes extremely high and almost unaffordable for a voter. To mitigate this issue, we allow transactions that invoke the cast-ballot function at line 12 of Algorithm 1 to be treated with equal priority and have priority over the rest of the transactions despite using a low gas price. This allows, voters to participate in the election without incurring high costs.

**Period of committee change.** As we already mentioned in Figure 2, SocChain starts a new configuration every \( x \) blocks, where \( x = 100 \) by default. However, as SocChain produces block on-demand (after receiving sufficiently many transactions), triggering the next reconfiguration could take a very long time, if for example transactions were issued rarely. Instead, we need to rapidly reconfigure SocChain so that \( n \) voters get re-elected before \( n/3 \) of them get corrupted through a bribery attack. Otherwise, an adversary could gain progressively the control of a coalition of \( n/3 \) or more voters to finally dictate the decisions to the rest of the blockchain nodes. To cope with this issue, we require every blockchain node offering the SocChain service to spawn \( \text{no-op} \) transactions on a regular basis (line 4 of Algorithm 4). As blockchain nodes get rewarded based on the service they offer, this reward can be used to compensate the loss associated by these \( \text{no-op} \) transaction fees. Provided that the clock skews between correct blockchain nodes is bounded, then these \( \text{no-op} \) transactions should ensure that reconfiguration occurs sufficiently frequently to cope with bribery attacks.

**Privacy, pseudonymity and anonymity.** To maintain the integrity of the voting protocol and to prevent users from influencing one another, the voting protocol should remain anonymous [15]. As the smart contract is stored in cleartext in the blockchain data structures, a honest but curious adversary could easily map the public key of a voter to its cast ballot. This preserves pseudonymity: as long as this user does not link publicly its identity to its public key, then it remains anonymous. To offer strong anonymity, SocChain can be combined with a commit-reveal scheme [43, 77] or ring signature [16] to reveal the voter once the election terminates, or homomorphic encryption [67] or zk-SNARK [61] on top of SocChain.
pragma solidity ^0.4.0;
pragma experimental ABIEncoderV2;

contract Committee {
  string[] committee;
  address public chairperson;
  mapping(string => bool) hasIp;
  mapping(string => bool) hasCalled;
  mapping(address => string) WallettoIP;
  mapping(uint => string[]) ballots; // mapping between ballot number and the vote transferrable to the next round
  mapping(string => uint) votes;
  mapping(bytes32 => uint) rest;
  mapping(uint => string)[] ballots;
  mapping(string => uint) transfer;
  mapping(string => uint) tot-surplus;
  mapping(uint => uint) indexers;
  uint c-ballot;
  uint threshold;
  uint size;
  uint select;
  uint transfer;
  uint k;
  uint rest-tot;
  uint quota;
  uint min;
  uint eliminatedcount;
  uint round;
  bool val;
  bool excess;
  bool eliminated;
  bool elect;
  mapping(string => bool) elected;

  // initial set of node ips and the size of the committee is parse by the chairperson
  function addIp (string[] memory ip, uint members, string[] memory wallets) public {
    delete committee;
    require(msg.sender == chairperson, "Only chairperson can give right to vote.");
    // committee here is the initial set of nodes -- this is equal to candidates
    for (uint t = 0; t < ip.length; t++){
      committee.push(ip[t]);
      WallettoIP[parseAddr(wallets[t])] = ip[t];
      elected[ip[t]] = false;
      hasIp[ip[t]] = true;
      hasCalled[ip[t]] = false;
    }
    size = committee.length;
    member = members;
    threshold = size - (size - 1)/3;
    quota=(threshold/(member+1))+1;
    // members is the number of participants per committee
  }

  event notify(string[]);
  constructor() public {
    chairperson = msg.sender;
    c-ballot = 0;
  }

  // initial set of node ips and the size of the committee is parse by the chairperson
}
// you have to change this function according to STV

function createCommittee (string[] memory candidates) public {
  // if the caller of this function is in the list of ips added by the chairperson, and if they haven't call this function
  // before - because we don’t want t+1 be reached by a malicious node calling this function multiple times
  require(hasIp[WallettoIP[msg.sender]] == true & hasCalled[WallettoIP[msg.sender]] == false);
  hasCalled[WallettoIP[msg.sender]] = true;

  // check if the IPs of the candidates received are the same as the addIP candidates
  for(uint i=0; i<candidates.length; i++) {
    for(uint z=0; z<committee.length; z++) {
      if(keccak256(abi.encodePacked(candidates[i]))==keccak256(abi.encodePacked(committee[z]))){
        ballots[c-ballot].push(candidates[i]);
        votes[candidates[i]]=0;
        transfer-vote[candidates[i]]=0;
      }
    }
  }

  if(ballots[c-ballot].length !=0) {
    c-ballot=c-ballot + 1;
  }

  if(c-ballot == threshold) {
    // start doing stv
    for(uint a=0; a<c-ballot; a++) {
      ballot-index[a]=0;
    }
    round = 0;
    eliminatedcount=0;
    // first preference vote calculation
    for (a = 0; a<c-ballot; a++){
      votes[ballots[a][round]]=votes[ballots[a][round]]+1;
    }
    // do until the number of seats-members is filled
    while ((selected.length < member) & round<size) {
      // loop through ballot and count votes
      elect = false;
      excess = false;
      eliminated = false;
      // add changes from here //
      val=next-pref();
      if (val==true) {
        elect = true;
      }
      if (elect == false) {
        // remove least voted
        min = 100000;
        // minimum vote of all candidates (non elected) is eliminated
        for (a = 0; a<c-ballot; a++) {
          for(uint x=ballot-index[c-ballot]; x<size; x++) {
            if((votes[ballots[a][x]] < min) & !elected[ballots[a][x]]){
              min = votes[ballots[a][x]];
            }
          }
        }
        eliminate();
      }
      if (((size-eliminatedcount)==member) {
        break;
      }
      round = round + 1;
    }

    // to add the remainder of members //
    min = minimum();
    while((size-eliminatedcount) >member) {
      for (a = 0; a<c-ballot; a++) {
        for(x=0; x<size; x++) {
          if(votes[ballots[a][x]]==min & (size-eliminatedcount) >member & votes[ballots[a][x]]!=10000000){
            ballots[c-ballot].push(votes[ballots[a][x]]);
          }
        }
      }
    }
  }
}
votes[ballots[a][x]]=10000000;
eliminatedcount=eliminatedcount+1;
min = minimum();
}
}
}
}
// add the new section here - if the seats to be selected equals the non eliminated candidates (won and not yet elected),
// assign already non elected and non eliminated candidates to the seats and exit the loop.
if((size - eliminatedcount) == member) {
for(a = 0; a<c-ballot; a++) {
  for(x=0; x<size; x++) {
    if(votes[ballots[a][x]]!=1000000 & !elected[ballots[a][x]] & (selected.length)<member){
      selected.push(ballots[a][x]);
      elected[ballots[a][x]]=true;
    }
  }
}
emit notify(selected);
}

function minimum() returns (uint mins){
  mins = 100000;
  // minimum vote of all candidates is eliminated
  for (uint a = 0; a<c-ballot; a++){
    for(uint x=0; x<size; x++){
      if((votes[ballots[a][x]] < mins) & !elected[ballots[a][x]]){
        mins = votes[ballots[a][x]];
      }
    }
  }
  return mins;
}

function next-pref() public returns (bool elec){
  for (uint s=0; s<committee.length; s++) {
    transfer-vote[committee[s]]=0;
    tot-surplus[committee[s]]=0;
  }
  for (s=0; s<hashes.length; s++) {
    rest[hashes[s]] = 0;
  }
  surplus-current.length=0;
elec=false;
excess=false;
  if (selected.length < member) {
    for (s=0; s<c-ballot; s++) {
      for (uint x=ballot-index[s]; x<size; x++) {
        if (votes[ballots[s][x]]>=quota & votes[ballots[s][x]]!=1000000 & elected[ballots[s][x]] == false) {
          elected[ballots[s][x]] = true;
          selected.push(ballots[s][x]);
elect = true;
        transfer = votes[ballots[s][x]] - quota;
votes[ballots[s][x]]=quota;
        transfer-vote[ballots[s][x]] = transfer;
surplus-current.push(ballots[s][x]);
ballet-index[c-ballot]=x;
        excess = true;
      }
    }
  }
}
if (excess) {
  // break the surplus ballots to those that have the same surplus elected candidate
  for (uint a=0; a< c-ballot; a++) {
    indexes[a] = 7000;
  }
  for (uint j=0; j< c-ballot; j++) {
    for (k=0; k<surplus-current.length; k++) {
      if (keccak256(abi.encodePacked(ballots[j][ballot-index[j]])) == keccak256(abi.encodePacked(surplus-current[k]))) {
        x = 1;
        while ((ballot-index[j]+x) < size -1) {
          x = x + 1;
          if (!elected[ballots[j][ballot-index[j]+x]] & (ballot-index[j]+x) < size -2) {
            // mapping for ballot number => current indexer
            indexers[j]=ballot-index[j]+x; rest[keccak256(abi.encodePacked(ballots[j][ballot-index[j]],ballots[j][ballot-index[j]+x]))] = rest[keccak256(abi.encodePacked(ballots[j][ballot-index[j]],ballots[j][ballot-index[j]+x]))] + 1;
          }
          if ((ballot-index[j]+x) < size & rest[keccak256(abi.encodePacked(ballots[j][ballot-index[j]],ballots[j][ballot-index[j]+x]))] != 0 & !elected[ballots[j][ballot-index[j]+x]] & tot-surplus[ballots[j][ballot-index[j]]]!=0 & votes[ballots[j][ballot-index[j]]]!=10000000 & votes[ballots[j][ballot-index[j]+x]]!=10000000) {
            votes[ballots[j][ballot-index[j]+x]] = votes[ballots[j][ballot-index[j]+x]] + transfer-vote[ballots[j][ballot-index[j]]]* rest[keccak256(abi.encodePacked(ballots[j][ballot-index[j]],ballots[j][ballot-index[j]+x]))] / tot-surplus[ballots[j][ballot-index[j]]];
            rest[keccak256(abi.encodePacked(ballots[j][ballot-index[j]],ballots[j][ballot-index[j]+x]))] = 0;
          }
        }
      }
    }
  }
  // divide and add the transferred votes
  for(j=0; j< c-ballot; j++) {
    for(x=1; x<(size-1); x++) {
      if ((ballot-index[j]+x) < size & rest[keccak256(abi.encodePacked(ballots[j][ballot-index[j]],ballots[j][ballot-index[j]+x]))] != 0 & !elected[ballots[j][ballot-index[j]+x]] & tot-surplus[ballots[j][ballot-index[j]]]!=0 & votes[ballots[j][ballot-index[j]]]!=10000000 & votes[ballots[j][ballot-index[j]+x]]!=10000000) {
        votes[ballots[j][ballot-index[j]+x]] = votes[ballots[j][ballot-index[j]+x]] + transfer-vote[ballots[j][ballot-index[j]]]* rest[keccak256(abi.encodePacked(ballots[j][ballot-index[j]],ballots[j][ballot-index[j]+x]))] / tot-surplus[ballots[j][ballot-index[j]]];
        rest[keccak256(abi.encodePacked(ballots[j][ballot-index[j]],ballots[j][ballot-index[j]+x]))] = 0;
      }
    }
  }
  // moving the indexer to next
  for(a=0; a< c-ballot; a++){
    if(indexers[a]!=7000){
      ballot-index[a]=indexers[a];
    }
  }
  return elect;
}

function eliminate() {
  uint x;
  for (uint s=0; s<hashes.length; s++) {
    rest[hashes[s]] = 0;
  }
  for (uint a = 0; a< c-ballot; a++) {
    for (uint m=ballot-index[a]; m<size; m++) {
      if (votes[ballots[a][m]] == min & !elected[ballots[a][m]] & votes[ballots[a][m]] != 10000000 & !eliminated) {
        // if 0 just eliminate
        if (votes[ballots[a][m]] == 0) {
          votes[ballots[a][m]] = 10000000;
          eliminated=true;
          eliminatedcount=eliminatedcount+1;
        }
      }
    }
  }
}
// if it is the current index being eliminated

x = 1;

if ((m == ballot-index[a]) & (m < size - 1)) {
    while((elected[ballots[a][m+x]] || votes[ballots[a][m+x]] == 10000000) & (m+x) < (size - 1)) {
        x = x + 1;
    }
    if (!elected[ballots[a][m+x]] & votes[ballots[a][m+x]] != 10000000) {
        ballot-index[a] = m + x;
    }
}

break;

// otherwise //

x = 1;

if (m < (size - 1)) {
    while((elected[ballots[a][m+x]] || votes[ballots[a][m+x]] == 10000000) & (m+x) < (size - 1)) {
        x = x + 1;
    }
    if (!elected[ballots[a][m+x]] & (m+x) < size) {
        rest[keccak256(abi.encodePacked(ballots[a][m], ballots[a][m+x]))] =
        rest[keccak256(abi.encodePacked(ballots[a][m], ballots[a][m+x]))] + 1;
        hashes.push(keccak256(abi.encodePacked(ballots[a][m], ballots[a][m+x])));
    }
}

// transfer to the next preferences

for (a = 0; a < c-ballot; a++) {
    x = 0;
    while(x < (size - 1) & !eliminated){
        if (rest[keccak256(abi.encodePacked(ballots[a][x], ballots[a][x+1]))] != 0
            & votes[ballots[a][x]] == 10000000
            & votes[ballots[a][x+1]] == 10000000
            & !elected[ballots[a][x]]) {
            votes[ballots[a][x]] = votes[ballots[a][x+1]]
            + min*rest[keccak256(abi.encodePacked(ballots[a][x], ballots[a][x+1]))]
            / (votes[ballots[a][x]]);
            ballot-index[a] = x + 1;
            rest[keccak256(abi.encodePacked(ballots[a][x], ballots[a][x+1]))] = 0;
            votes[ballots[a][x]] = 10000000;
            eliminatedcount = eliminatedcount + 1;
            eliminated = true;
        }
        x = x + 1;
    }
}

}