

# SoK: Achieving State Machine Replication in Blockchains based on Repeated Consensus

Silvia Bonomi  
bonomi@diag.uniroma1.it  
Sapienza University  
Rome, Italy

Álvaro García-Pérez  
alvaro.garciaperez@cea.fr  
Université Paris-Saclay, CEA, List  
Palaiseau, France

Antonella Del Pozzo  
antonella.delpozzo@cea.fr  
Université Paris-Saclay, CEA, List  
Palaiseau, France

Sara Tucci-Piergiovanni  
sara.tucci@cea.fr  
Université Paris-Saclay, CEA, List  
Palaiseau, France

## ABSTRACT

This paper revisits the ubiquitous problem of achieving state machine replication in blockchains based on repeated consensus, like Tendermint. To achieve state machine replication in blockchains built on top of consensus, one needs to guarantee fairness of user transactions. A huge body of work has been carried out on the relation between state machine replication and consensus in the past years, in a variety of system models and with respect to varied problem specifications. We systematize this work by proposing novel and rigorous abstractions for state machine replication and repeated consensus in a system model that accounts for realistic blockchains in which blocks may contain several transactions issued by one or more users, and where validity and order of transactions within a block is determined by an external application-dependent function that can capture various approaches for order-fairness in the literature. Based on these abstractions, we propose a reduction from state machine replication to repeated consensus, such that user fairness is achieved using the consensus module as a black box. This approach allows to achieve fairness as an add-on on top of preexisting consensus modules in blockchains based on repeated consensus.

## CCS CONCEPTS

• Theory of computation → Distributed algorithms.

## KEYWORDS

blockchain, repeated consensus, censorship resistance, state machine replication, fairness

## 1 INTRODUCTION

The rise of blockchains [15, 29, 39, 48] in the last decade has revived the interest in distributed programming and Byzantine fault-tolerant systems. A blockchain [39] is an append-only, tamper-resistant distributed ledger of transactions organised in a chain of blocks, originally used for cryptocurrencies. Ethereum [48] popularised the concept of smart contracts as a mean to implement any application on top of a blockchain. These first proposals, however, have been criticised because the underlying blockchain protocol used to update the ledger, based on proof-of-work, is extremely energy consuming. New proposals then subsequently emerged

proposing alternatives to proof-of-work, including a notable number using standard Byzantine fault-tolerant distributed consensus (BFT consensus for short) [13, 33], for both the permissioned setting [22, 45, 47, 49] and the public permissioned one [10, 15, 29, 41]. This paper focuses on the alternatives in the permissioned and public permissioned setting. Thanks to the power of consensus, this blockchains are able to guarantee so-called absolute finality, which ensures that no value inserted into the ledger can ever be revoked. It has been shown that these blockchains, even though rarely accompanied by formal distributed systems specifications, can be built over standard distributed computing abstractions such as state machine replication [31] (SMR for short) or repeated consensus [18] (RC for short). Examples of such systems are Hyperledger [45], which builds a distributed ledger over SMR (in Hyperledger there is no notion of blocks), and Tendermint [10, 29]. Tenderbake [8] and Algorand [15], which build a blockchain over RC.

In case of a distributed ledger built on top of an SMR service (DL-SMR for short), transactions are interpreted as commands that are submitted directly by clients to the SMR service, while in case of a blockchain built on top of an RC service (BC-RC for short), transactions are collected by replicas into blocks, which are the input values that replicas propose to the RC service. Although the two approaches may seem equivalent at first sight since both produce a sequence of commands/transactions, they differ however in their ability to prevent *censorship*. In DL-SMR the SMR service decides on the order in which all the commands submitted by clients are eventually served. On the other hand, in BC-RC the RC service makes a series of *independent* decisions on each new block that is committed to the chain. The result is that in BC-RC a transaction submitted by a client could in principle be censored if replicas skip to include it into the blocks that they input to the underlying RC service.<sup>1</sup> Thus, client requests are never guaranteed to be committed to the sequence, and we say that RC lacks user fairness. Informally, user fairness guarantees that a transaction requested by a correct client will eventually be committed to the blockchain, unless the transaction becomes invalid by the insertion of other transactions into the blockchain while the requested transaction is still pending

<sup>1</sup>As described in [11], censorship has an impact on financial mechanisms such as *contracts for difference*, on *auditable computation*, and even on committee-based BFT consensus protocols, where censorship may enable a collusion of validators to prevent other validators from joining the consensus pool.

(see §3.1 for a formal definition). As customary [4, 8, 12, 16] validity is defined externally by a deterministic, application-dependent predicate.

The lack of user fairness above is pervasive in the setting of blockchains, since many of them are built on top of an RC service (e.g. [5, 10, 15, 29, 41, 47, 49]) and are therefore potentially vulnerable to censorship. As a consequence, these blockchains can only ensure user fairness under the assumption that all the proposers are correct.

Some of these blockchains [5, 10, 47, 49] improve the fairness guarantee by rotating the proposer, but this does not achieve user fairness, because there is no mechanism that ensures that an infinite number of correct proposers will be able to get their proposal agreed.

*Problem.* We tackle the problem of providing user fairness to blockchains built on top of RC in a seamless way. By seamless we mean that the property must be provided no matter the underlying consensus protocol implementing RC. Let us stress that, since blockchains are running systems today, techniques to implement them as replicated objects should be as lightweight and generic as possible to avoid to rewrite from scratch current running BFT consensus implementations.

*Contributions.* We systematise previous work by providing, for the first time, *complete and rigorous* specifications (properties and algorithms) of both DL-SMR and BC-RC constructions. We then prove that BC-RC does not solve DL-SMR in general, since the former construction lacks the user fairness property of the latter. To cover this gap, we introduce an abstraction for *fair repeated consensus* (FRC for short) that refines the RC abstraction, and we show that a correct implementation of FRC can be used to implement a blockchain built on top of it (BC-FRC for short) with user fairness. We then propose a reduction from FRC to RC, by aggregating *sub-proposals* that a replica hears of into a single proposal before inputting it to RC. We show that aggregating sub-proposals from  $f + 1$  or more contributors provides a form of *internal validity* (as opposed to the external validity of [4, 8, 12, 16]) that guarantees that the decided block contains at least one transaction that was proposed by a correct replica, which is an important ingredient to establishing that BC-FRC upholds user fairness.

Although the techniques used in this optimised transformation are not entirely novel, our solution is, to the best of our knowledge, the first one agnostic to the BFT consensus protocol in the underlying implementation of RC, and thus truly generic.

*Roadmap.* In §2 we state the system model and introduce some background on blockchains. In §3 we rigorously specify the DL-SMR and BC-RC constructions, and we analyse the relation between them and show that DL-SMR is strictly stronger than BC-RC. In order to close this gap, in §4 we introduce the FRC abstraction and the BC-FRC construction. We provide a reduction from FRC to RC and show that DL-SMR and BC-FRC are equivalent. In §5 we discuss previous definitions of fairness and existing techniques to achieve user fairness. In §6 we provide some concluding remarks.

## 2 PRELIMINARY DEFINITIONS

### 2.1 System model

We consider a message-passing distributed system composed of a potentially infinite set of processes  $\Pi$ . A process can have any of the roles of *client* or *replica*, i.e., the set  $\Pi$  can be partitioned into two (not necessarily disjoint) sets of clients and replicas respectively, and we assume that the cardinality of the latter set of replicas is always finite. The rest of our assumptions are conventional in the Byzantine model. We assume that the network is *partially synchronous*, i.e., the system operates asynchronously until some unknown Global Stabilisation Time (GST), after which, the system respects known and finite time bounds for computation and communication. Processes are equipped with a cryptographic primitive to sign all messages they send and we assume that signatures are not forgeable. In addition, we assume that channels are reliable and thus processes communicate with each other through authenticated perfect links. Processes may experience Byzantine failures, i.e., they may behave arbitrarily by omitting to send and receive messages, and by altering the content of messages. Such processes are said to be *faulty*. Processes that are not faulty are said to be *correct*. We let  $n$  and  $f$  be respectively the cardinality of the set of replicas and of the set of faulty replicas. We assume that  $f$  is strictly smaller than  $n/3$ , i.e., less than a third of the replicas are faulty.

### 2.2 Blockchain data structure

A blockchain (BC for short) is a distributed ledger with append-only and non-repudiation properties that consists of a replicated data structure composed of blocks. Each block contains a finite set of transactions and is placed into a sequence called *chain*.

Clients may interact with the BC by issuing requests to (i) read the content of the blockchain, or (ii) insert a new transaction  $tx$  into the blockchain. We focus on the latter requests, which are the ones that impact how blocks are created and inserted into the chain. A client issues a *transaction request* for transaction  $tx$  by invoking the *request(tx)* primitive.

Without loss of generality, we abstract away the notion of transaction, which may be a set of financial transactions or a set of operation calls on generic data. To this aim, we consider an application-defined validity condition on the transactions contained in the blocks that ensures that the every transaction is consistent with the semantics of the application implemented on top of the blockchain (e.g., no double spending in cryptocurrency blockchains) and that must be verified before a block is decided and inserted into the chain.

We consider *permissioned* blockchains, i.e., blockchains where the set of replicas who are in charge of maintaining the data structure is known *a priori*,<sup>2</sup> which ensures absolute finality (i.e., once a block is appended to the chain, it can never be revoked). A necessary condition to obtain absolute finality is that each new block appended to the chain is agreed upon with a BFT consensus protocol [6]. (Both BC-RC and DL-SMR use BFT consensus and fall under this category.)

<sup>2</sup>This assumption can be lifted by considering *committee-based* blockchains that allow for public, open access, where the set of participants is dynamically determined by a selection function that maps the current chain to a *committee* of replicas that are in charge of producing the next block [8, 29].

Correct clients are assumed to collectively issue an infinite number of transaction requests, but no client (correct or faulty) can issue an infinite number of requests in a finite period of time. Clients may issue transaction requests with a throughput that is higher than the one at which transactions can be allocated in the blockchain. We make no assumption on the amount of memory that each replica maintains, but we assume blocks to have bounded size.

We write  $\bar{b}$  to denote a chain that consists of an infinite sequence of blocks  $[b^0, b^1, b^2, \dots]$ , where  $b^i$  denotes the  $i$ -th block in the chain and  $\bar{b}^i$  denotes the prefix of the chain up to the  $i$ -th block. We sometimes decorate this notation with a replica subindex  $r$  to denote the chain (respectively the  $i$ -th block and the prefix of the chain) stored locally at replica  $r$ , as in  $\bar{b}_r$ ,  $b_r^i$  and  $\bar{b}_r^i$ . We write  $\langle \uparrow b, [tx_0, tx_1, \dots, tx_n] \rangle$  to denote a block that points to block  $b$  and contains the sequence of transactions  $tx_0$  to  $tx_n$ . We write  $\bar{b}^i \frown txs$  and  $\bar{b}^i :: [\langle \uparrow b^i, txs \rangle]$  as synonyms, which denote the chain obtained by concatenating to the prefix  $\bar{b}^i$  a block that contains the pointer  $\uparrow b^i$  to the last block in the prefix and the sequence of transactions  $txs$ .

The initial block  $b^0 = (\perp, [])$ , called the *genesis block*, is a special block that is known a priori by each correct replica and which contains an undefined pointer and an empty sequence of transactions.

Throughout the paper, we emphasise the data structure maintained by the replicas, which consists of the chains stored locally at each replica. We let the current chain  $\bar{b}$  be the longest common prefix of the chains that are stored at correct replicas, and assume that correct clients have at their disposal a deterministic primitive *read()* that retrieves the current chain, whose details are out of the scope of this paper.

We let each transaction to be uniquely identified, e.g., by letting it be timestamped and signed by the client that issued it. We say that a transaction  $tx$  issued by a client is *finalised* iff a block whose sequence of transactions contains  $tx$  is inserted into the current chain. Otherwise we say that transaction  $tx$  is *pending*.

### 3 DISTRIBUTED LEDGER CONSTRUCTIONS

In this section we provide rigorous specifications of the DL-SMR and BC-RC constructions. We propose a general framework for building RC-BCs that use RC as a building block.

#### 3.1 Distributed ledger over SMR (DL-SMR)

We consider a variant of the state machine replication (SMR) abstraction in [1, 2]. SMR specifies a strongly consistent replicated service given by a deterministic state machine with a set of commands that can be issued by clients. A set of replicas commits these commands into a linearisable log and produces a consistent result of applying them, which is akin to the execution of the service by a single correct replica that applies the commands in the order in which they occur in the log.<sup>3</sup>

Due to its nature, SMR can be directly used as a distributed ledger construction, to which we refer as DL-SMR. This can be achieved by viewing transactions as commands and logs as states, and by

<sup>3</sup>The definition of SMR in [1, 2] assumes that the operations can be linearised [26], which imposes a one-to-one correspondence between the operations in a history and those in its linearisation. We reuse this intuition but note that linearisability cannot be lifted to a Byzantine setting just as readily [35, 36].

considering that a transaction is finalised when it is committed (i.e., appended) to the log.

We use the notation for sequences that we introduced in §2.2 and write  $\bar{\ell}$  for the log,  $\ell^k$  for the transaction at position  $k$  of the log, and  $\bar{\ell}^k$  for the prefix of the log up to position  $k$ . (Mind that a position  $k$  of the log refers to an individual transaction, as opposed to a block in a blockchain, which may contain several transactions.) We may decorate the log  $\ell$  with a replica subindex  $r$  to denote the log stored locally at replica  $r$ , as in  $\bar{\ell}_r$ ,  $\ell_r^k$  and  $\bar{\ell}_r^k$ .

Clients issue transactions through the primitive *submit(tx)*, and a correct replica may eventually commit some transaction  $tx$  for each position of the log given that  $tx$  is valid to the replica. Following the conventions on distributed ledgers [4, 8, 12, 16], we define validity of a transaction  $tx$  by employing an application-defined predicate *validLog()* that takes the log resulting by appending  $tx$  to the current log and returns true iff the transactions in the log are consistent with the semantics of the application implemented on top of the distributed ledger. We say that a transaction  $tx$  is *valid to replica  $r$  at position  $k$*  iff *validLog( $\bar{\ell}_r^{k-1} :: [tx]$ )* holds. We may omit the  $k$  and the  $r$  and write “valid to replica  $r$ ” or just “valid” when they are clear from the context.

After a correct replica  $r$  commits transaction  $tx$ , the replica applies the transaction by appending  $tx$  to the replica’s current log  $\bar{\ell}_r^k$ . We omit any notification to the client since we put the emphasis on the data structure (the log) maintained by each replica.

We require that DL-SMR meets the properties below:

- (*Safety*) Two correct replicas do not commit different transactions at the same log position.
- (*User fairness*) Let a correct client issue a transaction  $tx$  that is valid to some correct replica  $r$  at the moment when  $tx$  is issued. Either  $tx$  becomes invalid to  $r$  at some posterior moment, or otherwise  $tx$  is eventually finalised.
- (*Log validity*) If  $\bar{\ell}_r^k$  is the current log of a correct replica  $r$ , then *validLog( $\bar{\ell}_r^k$ )* holds.
- (*Log finality*) A correct replica commits at most one transaction for each position in the log.

*Safety* above corresponds to the property with the same name in [1, 2]. Our *User fairness* above characterises when a transaction issued by a correct client will be finalised, which differs from *User fairness* in [46] which states that the quality of the chain is such that at least one half of the transactions that it contains has been issued by correct clients.<sup>4</sup> When assuming that every client is correct and that every transaction is valid to every replica—i.e., *validLog* is the constant predicate that always returns true—then our *User fairness* coincides with *Liveness* in [1, 2].<sup>5</sup> The last two properties of DL-SMR above correspond respectively to the *Validity* and *Integrity* properties of [46].

For simplicity, when considered in the context of blockchain implementations, we let the logs in DL-SMR correspond to chains by letting each transaction in the log to be contained in a different

<sup>4</sup>In [46] they assume the fully asynchronous model which we do not, and thus our specification and theirs are incomparable in strength.

<sup>5</sup>We observe however that although *Liveness* in [1] states that “every request is eventually committed by honest replicas”, Thm.4 of that work only proves liveness for honest replicas, stated as “all honest replicas keep committing requests”.

block. Formally, a  $\log \ell^k$  of length  $k$  corresponds to a chain  $\overline{b^{k+1}}$  of length  $k+1$  where  $b^0$  is the genesis block which does not contain any transactions and which is known to every correct replica, and each block  $b^i$  with  $i > 0$  points to  $b^{i-1}$  and contains the single transaction  $\ell^{i-1}$ , which is the transaction at position  $i-1$  in the log. To wit, the log  $[tx_0, tx_1]$  corresponds to the chain  $[\langle \perp, [] \rangle] \cap [tx_0] \cap [tx_1]$ .

Next, we discuss the alternative RC-BC construction, which is customary in the blockchain setting. We start by presenting its RC building block.

### 3.2 Repeated consensus (RC)

We consider a variant of the repeated consensus (RC) abstraction in [18]. RC consists of an infinite sequence of instances of BFT consensus which altogether decide an infinite sequence of values. Without loss of generality, we will consider blocks as values and let the sequence of decided values coincide with the chain. At each consensus instance  $i$ , each correct replica inputs a block  $b$  through the primitive  $\text{input}(i, b)$  (note that the block  $b$  may be different from the inputs of other replicas) and eventually outputs some decided block  $b'$  which is appended to the local chain stored by the replica. We let each replica sign the block that the replica inputs at each consensus instance, such that every participant could check the provenance of each decided block (the replica who proposed the block).

As before, we capture the validity of a decided block  $b$  by employing an application-defined predicate  $\text{validChain}()$  that takes the whole chain ending with  $b$  and returns true iff the chain is well-formed and its transactions are consistent with the semantics of the application implemented on top of the blockchain. We say that a block  $b$  is *valid to replica  $r$  at consensus instance  $i$*  iff  $\text{validChain}(\overline{b_r^{i-1}} :: [b])$  holds. We may omit the  $i$  and the  $r$  and write “valid to replica  $r$ ” or just “valid” when they are clear from the context.

We require that RC meets properties below:

- (*Agreement*) If  $\overline{b_r}$  and  $\overline{b_s}$  are respectively the current outputs of two correct replicas  $r$  and  $s$ , then either  $\overline{b_r}$  is a prefix of  $\overline{b_s}$ , or  $\overline{b_s}$  is a prefix of  $\overline{b_r}$ .
- (*Termination*) Every correct replica has an infinite output.
- (*Chain validity*) If  $\overline{b_r^i}$  is the current output of a correct replica  $r$ , then  $\overline{b_r^i}$  is signed by some replica  $r'$  (not necessarily different from  $r$ ) and  $\text{validChain}(\overline{b_r^i})$  holds
- (*Chain finality*) A correct replica outputs at most one block for each consensus instance.

The first two properties of RC adapt the properties with the same name in [18]. *Chain validity* states that each new block is well-formed and upholds the semantics of the application implemented on top of the blockchain, and *Chain finality* collects the absolute finality assumption for permissioned blockchains.

### 3.3 Blockchain over RC (BC-RC)

A *blockchain over repeated consensus* (BC-RC) is a blockchain implemented on top of a correct implementation of RC, for which we require the four properties of *Agreement*, *Termination*, *Chain validity* and *Chain finality*, and which additionally meets the properties below:

---

#### Algorithm 1: BC-RC Client $c$

---

```

1 procedure  $\text{request}(tx)$ 
2    $\overline{b^i} \leftarrow \text{read}()$ ;
3   if  $\text{validChain}(\overline{b^i} \cap [tx])$  then send  $\langle \text{REQ}, tx \rangle$  to every replica;
```

---



---

#### Algorithm 2: BC-RC Replica $r$

---

```

1  $\text{pool} \leftarrow []$ ; // Initialisation
2 upon received  $\langle \text{REQ}, tx \rangle$  from a client
3    $\text{pool} \leftarrow \text{pool} :: [tx]$ ;
4 upon  $\text{RC.output}(i)$ 
5   clear transactions in  $\text{RC}.\overline{b_r^i}$  from  $\text{pool}$ ;
6    $txs \leftarrow$  pick from  $\text{pool}$  up to block size and valid to  $\text{RC}.\overline{b_r^i}$ ;
7    $\text{RC.input}(i+1, \langle \uparrow(\text{RC}.\overline{b_r^i}), txs \rangle)$ ;
```

---

(*Valid request*) If a correct client sends a request to insert a transaction  $tx$  to some replica, then  $\text{validChain}(\overline{b^i} \cap [tx])$  holds where  $\overline{b^i}$  is the current chain at the moment when the client sends the request.

(*Valid input*) If a correct replica inputs a block  $b$  for some consensus instance, then for each transaction  $tx$  contained in  $b$  there exists some client from which the replica received a request to insert  $tx$ .

The two additional properties above characterise the interaction between BC-RC and the RC building block, not the behaviour that is externally observable from the output of BC-RC. In particular, *Valid request* enforces that the requests received from a correct client are valid with respect to the current chain at issuing time,<sup>6</sup> and *Valid input* enforces that correct replicas do not input spurious transactions created out of thin air.

Alg. 1–2 respectively collect the code for the client and the replica of a generic BC-RC, which takes a correct implementation of RC as parameter. At a correct client, the primitive  $\text{request}(tx)$  (Lin.1 of Alg.1) first retrieves the current chain  $\overline{b^i}$  (Lin.2) and then sends a request  $\langle \text{REQ}, tx \rangle$  to insert transaction  $tx$  to all the replicas, given that the transaction is valid with respect to the current chain (Lin.3), thus upholding *Valid request*.

Each correct replica initialises a pool of pending transactions to the empty sequence (Lin.1 of Alg.2). Upon the reception of a request  $\langle \text{REQ}, tx \rangle$  from a client, the replica collects the transaction  $tx$  into the pool (Lin.2–3). Once a new block is output at consensus instance  $i$  (Lin.4) the replica first clears the finalised transactions in the chain up to that block (Lin.5), and assembles into a proposed block some of the valid transactions in the pool (not necessarily all, since the size of blocks is bounded)<sup>7</sup> and moves to consensus instance  $i+1$  by inputting the proposed block (Lin.6–7). *Valid input* holds since the transactions have been picked from the pool and the pool collects transactions received from clients. The implementation of RC provides the local chain  $\text{RC}.\overline{b_r}$ , and the primitive

<sup>6</sup>We assume a deterministic primitive procedure  $\text{read}()$  at client side that retrieves the current chain.

<sup>7</sup>We intentionally under-specify how the valid transactions are picked and the invalid ones are cleared from the pool, which may be application-defined.

procedure  $\text{RC.input}(i, b)$  and notification  $\text{RC.output}(i)$ . We assume that every replica starts its execution by notifying the output of the genesis block at consensus instance 0.

We next study in depth the relation between DL-SMR and BC-RC.

### 3.4 The relation between DL-SMR and BC-RC

Although both the BC-RC and the DL-SMR constructions implement a distributed ledger, the two constructions differ in the key property of user fairness. BC-RC focuses on the blocks being output at each consensus instance (the data structure), and places no relation between each committed block and how the block was produced or by whom (which clients issue which transactions, and how these are assembled into blocks by replicas). By contrast, DL-SMR places such a relation and assumes that every transaction issued by a correct client will either become invalid at some moment, or otherwise it will be committed by all correct replicas. This is a stronger property cannot be achieved by RC-BC alone.

We consider *reducibility* among distributed problems as in [14, 38], which we define formally as follows. Let  $A$  and  $B$  be the specifications of two different distributed problems (i.e., two different distributed abstractions). We say that  $A$  *reduces to*  $B$  iff the existence of a solution of  $A$  entails the existence of a solution of  $B$ . (In practice, a reduction from  $A$  to  $B$  is witnessed by a correct implementation of  $B$  that uses any correct implementation of  $A$  as a blackbox.) We say that  $B$  is *at least as strong as*  $A$  iff  $A$  reduces to  $B$  (i.e., existence of a correct implementation of  $B$  guarantees the existence of a correct implementation of  $A$ ). We say  $B$  is *strictly stronger than*  $A$  iff  $A$  reduces to  $B$  and  $B$  is not reducible to  $A$ . We say  $A$  and  $B$  are *equivalent* iff  $A$  reduces to  $B$  and  $B$  reduces to  $A$ .

Lem.3.1–3.2 below state that DL-SMR is strictly stronger the RC-BC, since RC-BC reduces to DL-SMR but not the converse.

LEMMA 3.1. *BC-RC is reducible to DL-SMR.*

PROOF. Assume a correct implementation of DL-SMR. We produce a correct implementation of BC-RC as follows. We fix a genesis block  $b^0$  and let every correct replica output it. Upon the invocation of  $\text{request}(tx)$  by a correct client, we let the client trigger the primitive  $\text{submit}(tx)$  of DL-SMR. We let the predicate  $\text{validChain}$  coincide with  $\text{validLog}$  when the log produced by SMR is viewed as a chain as in the correspondence detailed in §2. It suffices to show that *Agreement*, *Termination*, *Chain validity* and *Chain finality* hold, since *Valid request* and *Valid input* are internal properties of BC-RC, not observable from the output of the abstraction. *Agreement*, *Chain finality* and *Chain validity* hold respectively by *Safety*, *Log validity* and *Log finality*. It is easy to see that *Termination* follows by *User fairness* since, collectively, the correct clients issue an infinite number of transactions, and a correct client issues  $\text{request}(tx)$  only if the transaction  $tx$  is valid with respect to the current chain, which upholds the  $\text{validChain}$  predicate. It could happen that for each transaction issued by a correct client, there exists a Byzantine client with good bandwidth that issues another transaction that invalidates the one from the correct client, preventing the latter from ever being committed. Although this very improbable scenario is pathological, *Termination* would still hold because the output of correct replicas will be infinite since we assume that correct clients collectively issue an infinite number of transactions.  $\square$

LEMMA 3.2. *DL-SMR is not reducible to BC-RC.*

PROOF. We show that producing an implementation of DL-SMR that upholds *User fairness* from a correct implementation of BC-RC without adding any synchronisation complexity is not possible in general: the implementation of BC-RC could always neglect the requests of a particular correct client, such that the transactions issued by that client would never be finalised.  $\square$

Figure 1 summarises the content of Lem.3.1–3.2.

## 4 ACHIEVING USER FAIRNESS

Lem.3.2 from §2 sustains that BC-RC does not solve DL-SMR in general, since BC-RC does not uphold the *User fairness* property. To cover this gap, we introduce the *Fair Repeated Consensus* abstraction (FRC for short), which refines RC, and the construction for building a blockchain over FRC (BC-FRC for short).

### 4.1 Fair repeated consensus (FRC)

In order to formalize *fair repeated consensus* (FRC), we need to introduce the following preliminary definitions. We consider an external  $\text{validChain}$  predicate as in RC of §3 and, additionally, we let the external fusion  $(\bar{b}^i, (\bar{t}_j)_{j \in I})$  be a deterministic, application-defined function that takes the current chain  $\bar{b}^i$  and a collection of sequences of transactions  $(\bar{t}_j)_{j \in I}$ , and fuses the collection into a result sequence  $\bar{t}$  that contains valid transactions.

The FRC abstraction that we introduce below refines the RC abstraction from §3.2. FRC shares interface and properties with RC, and additionally meets the following:

(*Fair fusion*) Let  $\bar{b}^i$  be a chain,  $(\bar{t}_j)_{j \in I}$  a collection of sequences of transactions, and  $\bar{t}$  be the result sequence returned by  $\text{fusion}(\bar{b}^i, (\bar{t}_j)_{j \in I})$ . For every transaction  $tx$  that occurs in some sequence  $\bar{t}_j$  in the collection, either  $tx$  occurs in the result  $\bar{t}$ , or otherwise there exists a position  $k$  of  $\bar{t}$  such that  $\text{validChain}(\bar{b}^i \frown (\bar{t}^k :: [tx]))$  does not hold.

(*Fusion validity*) If a correct replica  $r$  outputs a block at some consensus instance  $i$ , then the sequence of transactions contained in that block coincides with the fusion of the sequences in the input blocks of  $f + 1$  or more replicas.

*Fair fusion* collects the intuition that the fusion function should include in its result the transactions in the collection of sequences that uphold the external validity predicate.

*Fusion validity* adapts *Vector validity* from [20] to our setting and relaxes the threshold of contributors  $2f + 1$  in [20] to  $f + 1$  (i.e., each output block must contain transactions coming from at least  $f + 1$  contributors). Notice that *Fusion validity* abstracts from the way the inputs from replicas are aggregated into a result by using the fusion function, while *Vector validity* imposes that the inputs of the contributors are atomic, and that the result contains at most one value for each replica in the system.

The fusion function and the validity predicate of FRC could be instantiated to cover a varied spectrum of order-fairness models. At one end of the spectrum we could place the rather general model of Bitcoin [39], which considers no transaction ordering

DL-SMR (in:  $client.submit(tx) \mid out: \bar{\ell}$ )  
Safety, User fairness, Log validity, Log finality.

$\supset$

BC-RC (in:  $client.request(tx) \mid out: \bar{b}$ )  
Valid request, Valid input.

RC (in:  $replica.input(b) \mid out: \bar{b}$ )  
Agreement, Termination, Chain validity, Chain finality.

**Figure 1: Relation among DL-SMR, BC-RC and RC (symbol  $\supset$  indicates that BC-RC reduces to DL-SMR but not the converse).**

#### Algorithm 3: FRC Replica $r$

```

1  $done \leftarrow 0;$  // Initialisation
2 procedure  $input(i, b)$ 
3    $txs \leftarrow$  transactions in  $b$ ;
4   send  $\langle SUB-PROP, r, i, txs \rangle$  to every replica;
5 upon received  $\langle SUB-PROP, s, i, txs_s \rangle$  from each  $s \in S$  with  $|S| \geq f + 1$ 
   and  $done = i - 1$ 
6    $txs \leftarrow fusion(RC.b_r^{i-1}, (txs_s)_{s \in S});$ 
7    $done \leftarrow i;$ 
8    $RC.input(i, \langle \uparrow(RC.b_r^{i-1}), txs \rangle);$ 
9 upon  $RC.output(i)$ 
10  trigger  $output(i);$ 

```

within a block (akin to a set of transactions where every transaction commutes with each other) and where causality of a transaction is only with respect to the previous blocks (i.e., the predicates  $\forall tx \in txs. validChain(\bar{b}^i \frown [tx])$  and  $validChain(\bar{b}^i \frown txs)$  are synonymous). At the other end of the spectrum we could place the rather specific model of Aequitas [27], which considers a transaction ordering that contains no loops except in some fragments of the sequence where every transaction is output “before or at the same time as” each other, and which best approximates *receive-order* while avoiding the Condorcet paradox.

FRC can be achieved with a correct implementation of RC. One direct way to reduce FRC to RC is to add an extra communication round that performs the aggregation of the sub-proposals that are input at FRC into an aggregated proposal that is input at the RC component. Alg.3 above presents such a reduction by implementing FRC on top of a correct implementation of RC. When a replica invokes the primitive  $input(i, b)$  at FRC (Lin.2 of Alg.3), it sends a sub-proposal for block  $b$  to every other replica. After receiving  $f + 1$  or more sub-proposals at consensus instance  $i$  (Lin.5) a replica aggregates the received sub-proposals into a single proposal (Lin.6), marks that the aggregation at consensus instance  $i$  has been done (Lin.7), and inputs a block with the aggregated proposal at the RC component (Lin.8). We assume that fusion in line 8) is such that *Fair fusion* holds. We require the  $validChain$  predicate of the RC component to be extended with a check that the input block has been contributed by  $f + 1$  or more replicas. This check can be achieved by collecting the signed sub-proposals that have been aggregated together with the aggregated proposal in the input block.<sup>8</sup> Once the RC component triggers the notification that the

<sup>8</sup>Checking that the input block has been contributed by enough replicas can be optimised by letting the replicas sign each individual transaction within a sub-proposal, or by tailoring some multi-signature scheme.

#### Algorithm 4: BC-FRC Client $c$

```

1 procedure  $request(tx)$ 
2    $\bar{b}^i \leftarrow read();$ 
3   if  $validChain(\bar{b}^i \frown [tx])$  then send  $\langle REQ, tx \rangle$  to every replica;

```

#### Algorithm 5: BC-FRC Replica $r$

```

1  $pool \leftarrow [];$  // Initialisation
2 upon received  $\langle REQ, tx \rangle$  from a client
3    $pool \leftarrow pool \cup [tx];$ 
4 upon  $FRC.output(i)$ 
5   clear transactions in  $FRC.b_r^i$  from  $pool$ ;
6    $txs \leftarrow$  pick in FIFO order from  $pool$  up to block size and valid to
    $FRC.b_r^i$ ;
7    $FRC.input(i + 1, \langle \uparrow(FRC.b_r^i), txs \rangle);$ 

```

block at consensus instance  $i$  has been output, the replica forwards this notification at FRC (Lin.9–10).

LEMMA 4.1. *FRC reduces to RC.*

PROOF. Assume a correct implementation of RC. We show that Alg.3 is a correct implementation of FRC. *Agreement*, *Termination*, *Chain validity* and *Chain finality* hold by the properties of RC with the same name. It is enough to show that *Fair fusion* and *Fusion validity* hold. At each consensus instance  $i$ , *Chain validity* ensures that the decided block  $b^i$  is signed by some correct replica  $r$ . By line 5 replica  $r$  aggregated contributions from  $f + 1$  or more sub-proposals and *Fusion validity* holds. By line 6, replica  $r$  used the fusion function for aggregating the sub-proposals and *Fair fusion* holds, and we are done.  $\square$

## 4.2 Blockchain over FRC (BC-FRC)

A *blockchain over fair repeated consensus* (BC-FRC for short) is a blockchain implemented on top of a correct implementation of FRC, for which we require the five properties of *Agreement*, *Termination*, *Chain finality*, *Fair fusion* and *Fusion validity*. We also require the *Valid request* and *Valid input* properties of BC-RC in §3.3, together with the additionally properties below:

(*Request agreement*) If a correct client issues a transaction  $tx$  then every correct replica eventually receives the request to insert  $tx$ .

(*Stubborn input*) If a correct replica  $r$  receives a request to insert a pending transaction  $tx$  at consensus instance  $i$  then there exists a consensus instance  $i_0 \geq i$  such that

- (i)  $tx$  is already finalised at consensus instance  $i_0$ , or
- (ii) there exists a position  $k$  such that

$$\text{validChain}(\overline{b_r^{i_0-1}} \frown (\overline{txs} :: [tx]))$$

does not hold, where  $txs$  is the sequence of transactions in the block that the replica  $r$  inputs at consensus instance  $i_0$ , or

- (iii) for every  $i' \geq i_0$  the replica  $r$  inputs a block that contains  $tx$  at consensus instance  $i'$ .

Alg.4–5 below introduce the client and the replica of a generic BC-FRC.

The FRC parameter ensures *Fair fusion* and *Fusion validity*. Besides requiring an implementation of FRC, the generic BC-FRC only differs from Alg.1–2 in Line 6 of Alg.5, which enforces that the replicas pick the transactions from the pool in FIFO order, thus upholding *Stubborn input*.<sup>9</sup> Notice that *Request agreement* holds trivially by the assumption of a reliable network. All these properties are sufficient for BC-FRC to uphold *User fairness*.

Our main contribution is collected in Lem.4.2 below.

LEMMA 4.2. *BC-FRC enjoys User fairness.*

PROOF. Assume a correct client issues a transaction  $tx$  that is valid with respect to some correct replica  $r$ . If  $tx$  ever becomes invalid afterwards, then we are done. Otherwise, we consider the case where  $tx$  never becomes invalid with respect to any correct replica, and show that  $tx$  will be eventually finalised.

Now, assume towards a contradiction that  $tx$  is never finalised. By *Request agreement* each correct replica  $r$  eventually receives the request to insert  $tx$  at some consensus instance  $i_r$ . Let  $i$  be the biggest among the  $i_r$ 's. By *Stubborn input*, there exists a consensus instance  $i_0 \geq i$  such that for each correct replica  $r$  one of the three conditions of the *Stubborn input* property of §4.2 is true. Condition (i) and (ii) cannot be true for any correct replica, because it is straightforward to derive a contradiction to our assumptions from them. Therefore, *Stubborn input* guarantees that Condition (iii) will be true for every correct replica, this is, each correct replica  $r$  inputs a block that contains  $tx$  at every consensus instance  $i' \geq i_0$ . By *Fusion validity*, the decided block  $b^{i_0}$  at consensus instance  $i_0$  is contributed by  $f + 1$  or more replicas, and therefore there is at least one correct replica who contributed to  $b^{i_0}$  whose sub-proposal contains  $tx$ . By *Fair fusion*, transaction  $tx$  is in the sequence of the decided block  $b^{i_0}$  or otherwise  $tx$  would have become invalid, which we assumed it never happens. This means that  $tx$  is output at consensus instance  $i_0$ , and by *Chain finality*, the transaction  $tx$  will never be revoked, hence it is finalised, which results in a contradiction and we are done.  $\square$

In the next subsection we detail the relations among the DL-SMR, BC-FRC, FRC and RC, and we show that DL-SMR and BC-FRC are equivalent, since they reduce to each other.

### 4.3 Equivalence of DL-SMR and BC-FRC

The fairness guarantees provided by BC-FRC warrant the reduction from DL-SMR to BC-FRC.

LEMMA 4.3. *DL-SMR is reducible to BC-FRC.*

PROOF. Assume a correct implementation of BC-FRC. We produce a correct implementation of DL-SMR as follows. Upon the invocation of  $\text{submit}(tx)$  by a correct client, we let the client trigger the primitive  $\text{request}(tx)$  of BC-FRC. We let the predicate  $\text{validLog}$  coincide with  $\text{validChain}$  when the chain produced by BC-FRC is viewed as a log by concatenating the sequences of transactions contained in the blocks in the order they occur in the chain.

*Safety* holds by *Agreement* when considering that a replica commits a transaction  $tx$  when it outputs a block whose sequence of transactions contains  $tx$ . (Without loss of generality, we let the replica commit at once all the consecutive log positions that correspond to appending to the current log the sequence of transactions in the output block.) *User fairness* holds by Lem.4.2 and by our choice of  $\text{validLog}$  and the correspondence between chains and logs. *Log validity* holds by *Chain validity* and by our choice of  $\text{validLog}$ , and *Log finality* holds by *Chain finality*.  $\square$

Lem.4.3 above helps to show that DL-SMR and BC-FRC solve essentially the same problem.

THEOREM 4.4. *DL-SMR and BC-FRC are equivalent.*

PROOF. We show that DL-SMR and BC-FRC are reducible to each other. The left-to-right direction is a direct consequence of Lem.4.3. For the right-to-left direction, we assume a correct implementation of BC-FRC and show how to produce a correct implementation of DL-SMR. Upon the invocation of  $\text{submit}(tx)$  by a correct client, we let the client trigger the primitive  $\text{request}(tx)$  of BC-FRC. We let the predicate  $\text{validLog}$  coincide with  $\text{validChain}$  when we consider that a chain corresponds to the log that results from appending the sequences of transactions in the blocks in the same order. *User fairness* holds by Lem.4.2. The properties of *Safety*, *Log validity* and *Log finality* hold respectively by *Agreement*, *Chain validity* and *Chain finality* and by our choice of  $\text{validLog}$ , and we are done.  $\square$

Figure 2 summarises the content of Lem.4.1–4.3 and Thm.4.4

Our solution relies on five conditions that encompass the issuing of transactions by clients, the collection of these transactions into blocks by replicas, the input of a block to the RC service at each replica, and the output of the decided block at each replica. More precisely, our solution requires the following:

- (1) All correct replicas eventually receive all the transactions issued by correct clients.
- (2) The correct replicas collect the transactions they receive in order, and they will stubbornly input blocks that contain these transactions in receive order, until each of the transactions is either finalised or has become invalid with respect to the current chain.

<sup>9</sup>Differently from Alg.2 in §2, Alg.5 here specifies a straightforward mechanism for handling pending transactions: traverse the pool in FIFO order while picking valid ones. We are however agnostic to other more speculative mechanisms for handling pending transactions that the blockchain model may stipulate, which ought to preserve *Stubborn Input*.

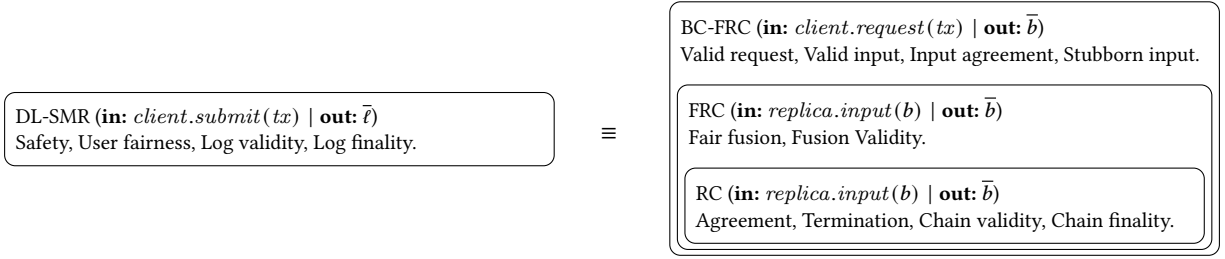


Figure 2: Relation among DL-SMR, BC-FRC, FRC and RC (symbol  $\equiv$  indicates that DL-SMR and BC-FCR reduce to each other).

- (3) At each correct replica, the RC service may aggregate inputs coming from different contributors (i.e., replicas) into a single block. In the vein of vector consensus [20], a replica will only output a decided block if it has been contributed by  $f + 1$  or more replicas,<sup>10</sup> which guarantees that the decided block is contributed by at least one correct replica.
- (4) We generalise vector consensus by considering a deterministic, application-dependent function fusion that takes several inputs and aggregates them into a single block. We require the decided block in (3) above to coincide with the aggregated block that results from applying fusion to the inputs of  $f + 1$  or more contributors. We make no particular assumptions on the order in which fusion places each of the transactions in the aggregated block, but we require that fusion does not drop any transaction unless including it in the aggregated block would make the block invalid with respect to the current chain. This provides great flexibility since the fusion function can capture different existing models for *order-fairness* [27].
- (5) The transactions that are inserted into the blockchain are never revoked. This requirement is always true for the BC-RC constructions in the permissioned setting that we consider, since the RC service is assumed to ensure absolute finality.

## 5 RELATED WORK

**Blockchains and SMR** The SMR problem, proposed in [31, 42] and generalized in [42], gained interest since Castro and Liskov [13] showed how to practically implement it in an eventually synchronous system in presence of Byzantine processes. Blockchains can be seen as a way to implement SMR, especially when they support smart contracts [48], i.e., pieces of executable code stored and executed in a replicated way in the blockchain. Nonetheless, to the best of our knowledge, no current market blockchain solution provides complete support for SMR. Libra [47] is one of the rare cases in which the blockchain is expressed as a construction over SMR, however the proposed SMR specification is restricted and does not encompass user fairness.<sup>11</sup> Interestingly, formalisations of

known blockchains put emphasis on the replicated data structure and its maintenance, but leave aside user fairness [6–8, 21]. Fairness in blockchains is generally desirable when participants of a blockchain have some stake into the system. An example of fairness can be found in the mutual exclusion problem, where fairness demands that all processes requiring to access the critical section must be eventually served [19, 30]. In the blockchain context the notion of fairness has mainly the connotations of

- *miner fairness*, which requires that processes that maintain the blockchain are rewarded proportionally to their amount of work, and
- *user fairness*, which requires that user requests are eventually served by the blockchain, in the spirit of fairness for mutual exclusion.

One of the first analysis in blockchain systems on miner fairness is the study of *chain quality*, which is defined by Garay *et al.* [21] as the proportion of blocks mined by honest miners in any given window. Other works that explored miner fairness are Ourobours *et al.* [28] and Fruitchain [40]. Although miner fairness can potentially affect user fairness, it is not a necessary condition to achieve user fairness, and therefore these previous works on chain quality do not close the gap that this paper focuses on.

Regarding user fairness, Gürcan *et al.* [23, 24] study Bitcoin and show that once a user issues a transaction (a request to the blockchain) there is no guarantee that such transaction will be committed to the blockchain. Herlihy and Moir [25] focus on blockchains based on BFT consensus—such as Tendermint and Libra—and discuss how malicious participants could violate user fairness by censoring transactions. Indeed, this is a common problem in such blockchains because the decided block for a given consensus instance could have been proposed by a Byzantine replica. To overcome this problem, in [25] they propose modifications to Tendermint’s algorithm to make user-fairness violations detectable and accountable.

To the best of our knowledge, Fairledger [34] is one of the first blockchains based on synchronous BFT consensus that explicitly provides user fairness. User fairness is guaranteed because at each consensus instance all the proposals are batched in a sole input value, so that either all of the transactions issued by clients are committed, or none of them are. In the same spirit, Honeybadger [37] uses an asynchronous component that implements randomized agreement, and batches together proposals from different replicas before inputting the aggregated proposal to the randomized agreement service. Moreover, they provide a probabilistic bound on the

<sup>10</sup> *Vector validity* requires the decided vector to contain  $2f + 1$  or more non-null elements, but for our purposes  $f + 1$  contributors is enough.

<sup>11</sup> In Libra SMR is expressed in terms of safety—all honest nodes observe the same sequence of commands—and liveness—new commits are produced as long as valid commands are submitted.



delay within which a request is committed, after the request has been received by enough correct processes.

Recently, in a parallel and independent work, Crain *et al.* [17] propose a solution similar to ours to achieve censorship-resistance in Red Belly. They aggregate the “valid and non-conflicting transactions” coming from  $f + 1$  proposers into a ‘superblock’ that is later input to the consensus module of Red Belly. They also introduce an abstraction for *Set Byzantine Consensus* which resembles our FRC, but their abstraction is specific for Red Belly’s cryptocurrency application since their notion of validity captures only that the transactions in the decided block do not exhaust the balance of any account. Our *Valid fusion* and *Fusion validity* properties allow for any generic-purpose application while capturing different existing approaches for fair-orderness [27]. We introduce a definition of SMR with a rigorous *User fairness* property and prove that our solution achieves SMR.

Techniques to achieve users fairness in BC-RC The approaches in both Fairledger and Honeybadger take inspiration from techniques emerged in the context of reductions of SMR to consensus. For instance, Honeybadger is an improvement in terms of communication complexity of the asynchronous atomic broadcast solution from Cachin *et al.* [12]. In [12] they show how to reduce atomic broadcast to consensus provided that the latter enjoys an external validity property that ensures that the decided value satisfies a validity predicate that can be verified locally by the replicas. Such an external validity property opens up for the possibility that a value complying with the validity predicate is decided, even if proposed by a Byzantine replica. This situation is customary in the blockchain setting, where a valid block (with respect to a local predicate) can be committed to the chain even if produced by a Byzantine process. The relevance of their work comes also from the fairness property provided by the atomic broadcast abstraction, which ensures that a payload message  $m$  is scheduled and delivered within a reasonable (polynomial) number of steps after it is atomically broadcast by an honest process. The techniques they use are in the spirit of Doudou and Shiper’s solutions for certified consensus and for atomic broadcast [20].

Milosevic *et al.* provide a thorough survey of reductions of atomic broadcast to RC in the Byzantine model, and analyse the validity property of different variants of RC to show which of them are equivalent to atomic broadcast [38].

Sousa and Bessani [44] provide an interesting solution of SMR in terms of an implementation of RC that, despite Byzantine replicas, guarantees that all operations from correct clients are always executed. To do so, they adapt the PBFT protocol [13, 43] in such a way that a leader change is triggered when a client transaction is not committed after a certain timeout, a fact that hints at the leader possibly being Byzantine. Note that Sousa and Bessani’s solution is not generic in the sense that it depends on the specific implementation of RC that they consider, while our generic solution applies to any implementation of RC and therefore it could be applied to any existing blockchain. In a similar vein, Prime [3] guarantees that once a correct replica gets to know about a transaction then such transaction is committed in a timely manner. Do to so, a Pre-Ordering phase precedes the PBFT consensus in charge to perform a global ordering on the transactions. Still in the SMR context, Bazzi and Herlihy propose Clairvoyant [9], a new solution to the problem

in the form of a protocol for the generalized consensus problem [32]. Interestingly, it provides liveness for all transactions under eventual synchrony and at all times for transactions that do not overlap with conflicting transactions. The solution leverages on non-skipping time stamps, which requires clients to interact with replicas to get the latest time stamp they observed before issuing a transaction. Their solution assumes  $4f + 1$  or more replicas, where  $f$  is the failure threshold. Close to us, there is a very recent work [50] that investigates how to avoid both transaction censorship and reordering despite the presence of Byzantine leaders proposing a block. To do so, when adding each block, two extra phases precede the consensus instance. Which, interestingly, can be any leader based consensus solution. Contrarily to us, [50], provides ordering but at the price of extra phases for each block creation. In our case we provide censorship resistance without transaction ordering guarantees adding only one extra phase for any leader based consensus solution.

## 6 CONCLUSION

In this work we analysed how to achieve state machine replication in blockchains based on repeated consensus. Our work systematises the huge body of work on state machine replication and its relationship with well-known distributed system problems such as Consensus and Atomic Broadcast. Our systematisation proposes formal abstractions to capture state machine replication and consensus implemented in blockchains, i.e. DL-SMR and BC-RC. We pointed out that what is missing in BC-RC to achieve DL-SMR is the user fairness property, stipulating that transactions issued by correct participants are eventually committed, if valid. We further introduced the FRC abstraction and a parametric BC-FRC construction, which enjoys user fairness, and state formally the equivalence between DL-SMR and BC-FRC. Notably our FRC abstraction relies on a fusion function and a validity predicate that could be instantiated to cover a varied spectrum of order-fairness models. Finally, we showed how to obtain DL-SMR out of RC in an agnostic way to the underlying consensus protocol and then truly modular.

## REFERENCES

- [1] Ittai Abraham, Dahlia Malkhi, Kartik Nayak, Ling Ren, and Maofan Yin. 2019. Sync hotstuff: Simple and practical synchronous state machine replication. *IACR Cryptology ePrint Archive* 2019 (2019), 270.
- [2] Ittai Abraham, Kartik Nayak, Ling Ren, and Zhuolun Xiang. 2020. Byzantine Agreement, Broadcast and State Machine Replication with Near-optimal Goodcase Latency. *CoRR* abs/2003.13155 (2020).
- [3] Yair Amir, Brian Coan, Jonathan Kirsch, and John Lane. 2010. Prime: Byzantine replication under attack. *IEEE transactions on dependable and secure computing* 8, 4 (2010), 564–577.
- [4] Yackolley Amoussou-Guenou, Antonella Del Pozzo, Maria Potop-Butucaru, and Sara Tucci-Piergiovanni. 2018. Correctness of Tendermint-core blockchains. In *Proc. Principles of Distributed Systems*.
- [5] Yackolley Amoussou-Guenou, Antonella Del Pozzo, Maria Potop-Butucaru, and Sara Tucci-Piergiovanni. 2019. Dissecting Tendermint. In *Proc. Networked Systems*.
- [6] Emmanuelle Anceaume, Antonella Del Pozzo, Romaric Ludinard, Maria Potop-Butucaru, and Sara Tucci-Piergiovanni. 2019. Blockchain abstract data type. In *The 31st ACM Symposium on Parallelism in Algorithms and Architectures*. 349–358.
- [7] Antonio Fernández Anta, Kishori M. Konwar, Chryssis Georgiou, and Nicolas C. Nicolaou. 2018. Formalizing and Implementing Distributed Ledger Objects. *SIGACT News* 49, 2 (2018), 58–76. <https://doi.org/10.1145/3232679.3232691>
- [8] Lăcrămioara Aștefanoaei, Pierre Chambart, Antonella Del Pozzo, Thibault Rieutord, Sara Tucci, and Eugen Zălinescu. 2021. Tenderbake – A Solution to Dynamic Repeated Consensus for Blockchains. In *Fourth International Symposium on Foundations and Applications of Blockchain 2021*.

- [9] Rida Bazzi and Maurice Herlihy. 2021. Clairvoyant state machine replication. *Information and Computation* (2021), 104701.
- [10] Ethan Buchman, Jae Kwon, and Zarko Milosevic. 2018. The latest gossip on BFT consensus. *CoRR* (2018). arXiv:1807.04938
- [11] Vitalik Buterin. 2015. The Problem of Censorship. (2015). <https://blog.ethereum.org/2015/06/06/the-problem-of-censorship/>.
- [12] Christian Cachin, Klaus Kursawe, Frank Petzold, and Victor Shoup. 2001. Secure and efficient asynchronous broadcast protocols. In *Annual International Cryptology Conference*. Springer, 524–541.
- [13] Miguel Castro and Barbara Liskov. 2002. Practical Byzantine Fault Tolerance and Proactive Recovery. *ACM Trans. Comput. Syst.* (2002).
- [14] T. D. Chandra and S. Toueg. 1996. Unreliable failure detectors for reliable distributed systems. *J. ACM* 43, 2 (1996), 225–267.
- [15] Jing Chen and Silvio Micali. 2019. Algorand: A secure and efficient distributed ledger. *Theor. Comput. Sci.* (2019).
- [16] T. Crain, V. Gramoli, M. Larrea, and M. Raynal. 2017. (Leader/Randomization/Signature)-free Byzantine Consensus for Consortium Blockchains.
- [17] Tyler Crain, Christopher Natoli, and Vincent Gramoli. 2021. Red Belly: a secure, fair and scalable open blockchain. *IEEE S&P*.
- [18] Carole Delporte-Gallet, Stéphane Devismes, Hugues Fauconnier, Franck Petit, and Sam Toueg. 2008. With Finite Memory Consensus Is Easier Than Reliable Broadcast. In *Proc. Principles of Distributed Systems*.
- [19] EW Dijkstra. 1965. A Solution of a Problem in Concurrent Programming Control. 8 (9): 569.
- [20] Assia Doudou and André Schiper. 1997. *Muteness Detectors for Consensus with Byzantine Processes*. Technical Report. in Proceedings of the 17th ACM Symposium on Principle of Distributed Computing, (Puerto).
- [21] J. A. Garay, A. Kiayias, and N. Leonardos. 2015. The Bitcoin Backbone Protocol: Analysis and Applications. In *Proc. EUROCRYPT International Conference*.
- [22] Vincent Gramoli. 2017. The red belly blockchain. *personal Communication, Facebook, USA*. (2017).
- [23] Önder Gürcan, Alejandro Ranchal Pedrosa, and Sara Tucci Piergiovanni. [n.d.]. On Cancellation of Transactions in Bitcoin-Like Blockchains. In *On the Move to Meaningful Internet Systems. OTM 2018 Conferences (Lecture Notes in Computer Science)*.
- [24] Önder Gürcan, Antonella Del Pozzo, and Sara Tucci Piergiovanni. 2017. On the Bitcoin Limitations to Deliver Fairness to Users. In *Proc. On the Move to Meaningful Internet Systems*.
- [25] Maurice Herlihy and Mark Moir. 2016. Enhancing Accountability and Trust in Distributed Ledgers. *CoRR* (2016).
- [26] Maurice Herlihy and Jeannette M. Wing. 1990. Linearizability: A Correctness Condition for Concurrent Objects. *ACM Trans. Program. Lang. Syst.* 12, 3 (1990), 463–492.
- [27] Mahimna Kelkar, Fan Zhang, Steven Goldfeder, and Ari Juels. 2020. Order-Fairness for Byzantine Consensus. *IACR Cryptol. ePrint Arch.* 2020 (2020), 269.
- [28] Aggelos Kiayias, Alexander Russell, Bernardo David, and Roman Oliynkov. 2017. Ouroboros: A Provably Secure Proof-of-Stake Blockchain Protocol. In *Proc. Advances in Cryptology*.
- [29] Jae Kwon and Ethan Buchman. [n.d.]. Cosmos: A Network of Distributed Ledgers.
- [30] Leslie Lamport. 1974. A New Solution of Dijkstra’s Concurrent Programming Problem. *Commun. ACM* 17, 8 (Aug. 1974), 453–455. <https://doi.org/10.1145/361082.361093>
- [31] Leslie Lamport. 1978. Time, Clocks, and the Ordering of Events in a Distributed System. *Commun. ACM* 21, 7 (1978), 558–565.
- [32] Leslie Lamport. 2005. *Generalized Consensus and Paxos*. Technical Report MSR-TR-2005-33. Microsoft Research (MSR).
- [33] L. Lamport, R. Shostak, and M. Pease. 1982. The Byzantine Generals Problem. *ACM Transactions on Programming Languages and Systems* (1982).
- [34] Kfir Lev-Ari, Alexander Spiegelman, Idit Keidar, and Dahlia Malkhi. 2019. FairLedger: A Fair Blockchain Protocol for Financial Institutions. *CoRR* abs/1906.03819 (2019). arXiv:1906.03819 <http://arxiv.org/abs/1906.03819>
- [35] Liskov and Rodrigues. 2005. Byzantine Clients Rendered Harmless (short). In *DISC: International Symposium on Distributed Computing*. LNCS.
- [36] Dahlia Malkhi, Michael K. Reiter, and Nancy A. Lynch. 1998. A Correctness Condition for Memory Shared by Byzantine Processes. (1998).
- [37] Andrew Miller, Yu Xia, Kyle Croman, Elaine Shi, and Dawn Song. 2016. The honey badger of BFT protocols. In *Proceedings of the 2016 ACM SIGSAC Conference on Computer and Communications Security*. 31–42.
- [38] Zarko Milosevic, Martin Hutle, and Andre Schiper. 2011. On the Reduction of Atomic Broadcast to Consensus with Byzantine Faults. In *Proc. 30th IEEE Symposium on Reliable Distributed Systems (30th SRDS’11)*. 235–244.
- [39] Satoshi Nakamoto. 2018. Bitcoin: A Peer-to-Peer Electronic Cash System. <https://bitcoin.org/bitcoin.pdf>.
- [40] Rafael Pass and Elaine Shi. 2017. FruitChains: A Fair Blockchain. In *Proc. ACM Symposium on Principles of Distributed Computing*.
- [41] Rafael Pass and Elaine Shi. 2018. Thunderella: Blockchains with Optimistic Instant Confirmation. In *Proc. Advances in Cryptology*.
- [42] Fred B Schneider. 1990. Implementing fault-tolerant services using the state machine approach: A tutorial. *ACM Computing Surveys (CSUR)* 22, 4 (1990), 299–319.
- [43] João Sousa, Eduardo Alchieri, and Alysson Bessani. 2013. State machine replication for the masses with BFT-SMaRt.
- [44] Joao Sousa and Alysson Bessani. 2012. From Byzantine consensus to BFT state machine replication: A latency-optimal transformation. In *2012 Ninth European Dependable Computing Conference*. IEEE, 37–48.
- [45] Joao Sousa, Alysson Bessani, and Marko Vukolic. 2018. A byzantine fault-tolerant ordering service for the hyperledger fabric blockchain platform. In *2018 48th annual IEEE/IFIP international conference on dependable systems and networks (DSN)*. IEEE, 51–58.
- [46] Alexander Spiegelman and Arik Rinberg. 2019. ACE: Abstract Consensus Encapsulation for Liveness Boosting of State Machine Replication. *arXiv preprint arXiv:1911.10486* (2019).
- [47] The LibraBFT Team. 2019. State Machine Replication in the Libra Blockchain.
- [48] Gavin Wood et al. 2014. Ethereum: A secure decentralised generalised transaction ledger. *Ethereum project yellow paper* 151, 2014 (2014), 1–32.
- [49] Maofan Yin, Dahlia Malkhi, Michael K Reiter, Guy Golan Gueta, and Ittai Abraham. 2019. HotStuff: BFT consensus with linearity and responsiveness. In *Proc. ACM Symposium on Principles of Distributed Computing*.
- [50] Yunhao Zhang, Srinath Setty, Qi Chen, Lidong Zhou, and Lorenzo Alvisi. 2020. Byzantine Ordered Consensus without Byzantine Oligarchy. In *14th {USENIX} Symposium on Operating Systems Design and Implementation ({OSDI} 20)*. 633–649.