

Enhancing Accountability and Trust in Distributed Ledgers*

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Abstract

Permissionless decentralized ledgers (“blockchains”) such as the one underlying the cryptocurrency Bitcoin allow anonymous participants to maintain the ledger, while avoiding control or “censorship” by any single entity. In contrast, *permissioned* decentralized ledgers exploit real-world trust and accountability, allowing only explicitly authorized parties to maintain the ledger. Permissioned ledgers support more flexible governance and a wider choice of consensus mechanisms.

Both kinds of decentralized ledgers may be susceptible to manipulation by participants who favor some transactions over others. The real-world accountability underlying permissioned ledgers provides an opportunity to impose fairness constraints that can be enforced by penalizing violators after-the-fact. To date, however, this opportunity has not been fully exploited, unnecessarily leaving participants latitude to manipulate outcomes undetectably.

This paper draws attention to this issue, and proposes design principles to make such manipulation more difficult, as well as specific mechanisms to make it easier to detect when violations occur.

1 Introduction

A *blockchain* is a data structure used to implement tamper-resistant distributed ledgers. Multiple *nodes* follow a common protocol in which transactions from *clients* are packaged into *blocks*, and nodes use a consensus protocol to agree on successive blocks. Each block’s *header* contains a cryptographic hash of the previous block’s header, making it difficult to tamper with the ledger. Bitcoin [20] is the best-known blockchain-based distributed ledger today.

In *permissionless* implementations, such as Bitcoin, any node willing to follow the protocol can participate, and anybody can generate addresses that can receive bitcoins, and can propose transactions that transfer bitcoins from any address for which they have the associated private key. By contrast, in *permissioned* implementations, the sets of participating nodes are controlled by an authority, perhaps one organization, perhaps a consortium.

A permissionless implementation makes sense for applications such as Bitcoin, which seek to ensure that nobody can control who can participate, a property often called *censorship resistance*. By contrast, permissioned implementations explicitly permit some forms of censorship: for example, permitting compliance with “know your customer” regulations that exclude known money-launderers from financial markets. Moreover, permissioned implementations can often provide more effective governance: for example, by providing an orderly procedure for updating the ledger protocol [11].

Here, we focus on one more important difference: permissioned ledgers can hold participants *accountable* for misbehavior in ways that permissionless implementations cannot. Many distributed ledgers would benefit from *fairness* guarantees. For example, one client’s proposed transactions should not be systematically delayed longer than others’, or one client’s transactions should not be systematically scheduled just

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after another’s competing transaction (say, front-running a stock purchase). While it may be difficult or impossible to flag a single instance of a fairness violation, systematic violations can be detected over time with high confidence. We say that a *fairness policy* is a technique for ensuring a *fairness guarantee*.

In permissionless ledgers, such as Bitcoin, an inherent lack of accountability makes fairness policies difficult to enforce. For example, in a *mining cartel attack* [6, 8, 22], a group of Bitcoin miners ignores transactions proposed by miners which are not members of that group. It can be difficult to detect such behavior, and even if detected, the cartel members suffer no effective penalty, other than perhaps public shaming and a loss of confidence in the ledger itself.

Even in permissioned ledgers, however, a participating node may violate a fairness policy because it has been hacked, its software is defective, its operator is dishonest, and so on. *In principle*, permissioned ledgers make it easier to hold nodes accountable for fairness policy violations: once exposed, a violator may lose a deposit, it may be expelled from the ledger, or it may be sued. In practice, however, reducing the opportunities for internal fairness violations, and detecting them when they occur, is a non-trivial problem that requires systematic scrutiny.

Our contribution is to call attention to this issue, and to propose principles for designing permissioned decentralized ledgers to hold participants accountable for fairness policy violations. To demonstrate that these principles apply to real systems, we propose a number of modifications to the open-source Tendermint [26] ledger system. Tendermint provides an effective platform for illustrating our ideas, but we believe our principles are applicable to a wide range of ledger implementations. We hope that both the general principles and the specific techniques we introduce will serve to alert the community to the importance of ensuring fairness properties in distributed ledgers, and to contribute to effective ways to do so.

Our approach is based on the following design principles.

- Each non-deterministic choice presents an opportunity to manipulate outcomes. As much as possible, non-deterministic choices should be replaced with deterministic rules, and mechanisms for detecting violations and holding the culprits accountable should be available.
- Non-deterministic choices that cannot be avoided should be disclosed in an auditable way, ensuring that they cannot be altered later, and that unusual statistical patterns can be detected.
- As much as possible, mechanisms that enhance accountability should be kept off the system’s critical path in order to avoid imposing substantial costs on normal-case execution by honest participants.

Sometimes, participants can be held accountable right away: posting a proof that a participant cheated may cause that participant to be expelled. Often, participants can be held accountable only after-the-fact. For example, sometimes one can detect that one of two interacting parties cheated, but it may not be immediately clear which one. Sometimes individual violations may be indistinguishable from legitimate non-determinism. In both cases, reducing opportunities for non-deterministic choices and systematically logging remaining ones can reveal suspicious long-term trends.

Section 2 presents background on the most relevant parts of Tendermint [26], the open-source distributed ledger system on which we base our design. Section 3 overviews our design, details of which are presented in Section 4. Discussion and related work appear in Sections 5 and 6, and we conclude in Section 7.

2 Background on Tendermint

In this section, we survey aspects of Tendermint [26] used to embody our ideas.¹ More complete descriptions are available elsewhere [24].

¹Our extensions build on commit `c318a227` from October 3, 2015. Since then, work on Tendermint has progressed, but as far as we can tell, later versions do not substantially change the issues addressed in this paper. Nonetheless details of integrating techniques we describe may differ given recent architectural changes in Tendermint [27].

Tendermint employs a peer-to-peer network in which nodes gossip information including: *transactions* submitted by clients, *blocks* of transactions proposed by *proposers*, and various messages used by the consensus protocol used to reach agreement among nodes on successive *next* blocks in the *chain* (blockchain). Honest validators vote only for blocks that satisfy certain validity conditions: for example, each block must include a cryptographic hash of the previous block, making it essentially impossible to change a block already committed into the blockchain.

Tendermint supports a notion of *accounts*, each of which has some number of associated *tokens*. Unlike Bitcoin, tokens are not created by proof-of-work mining. Instead, they are created by the first, or *genesis* block, or acquired out-of-band, perhaps by purchase.

Tendermint’s consensus mechanism is a variant of the PBFT Byzantine agreement algorithm [5, 25]. The current blockchain length is called its *height*. To add a new block of transactions to the chain, the protocol executes a sequence of *rounds*. At each height and round, a *proposer* proposes a block, and *validator* nodes vote whether to accept it. Further details are unimportant for our purposes: we use Tendermint’s consensus mechanism unmodified, and the techniques we present are not specific to the consensus protocol.

Tendermint uses a *proof of stake* (PoS) mechanism to keep validators honest. Each validator posts a bond, in the form of tokens, which it will lose if it is caught violating the protocol. If a validator is caught, proof of that transgression is posted to the blockchain, the culprit is expelled and its bond confiscated. (Others have discussed the strengths and weaknesses of PoS consensus [2].)

Here we are less concerned with the specific mechanisms used to punish participants that violate fairness constraints than how to reduce opportunities for such violations, and how to detect them when they occur.

Tendermint uses peer-to-peer gossiping to propagate consensus-related information including block proposals, votes, and other state information. Tendermint propagates block data in *parts*, using a protocol inspired by LibSwift [14], in which each block’s header contains the root of a Merkle tree [18]. The Merkle tree contains hashes of each block part, allowing confirmation that received block parts are valid.

The mechanisms described in this paper are independent of these aspects of Tendermint, with minor exceptions mentioned later. Next, we discuss in more detail several aspects of Tendermint that are more directly relevant to the mechanisms we present.

We focus here on the two transaction types of most direct interest to users. `SendTx` transactions send tokens from one or more *input* accounts to one or more *output* accounts. `CallTx` transactions create *contracts*, expressed as Ethereum [7] virtual machine byte code. Each such transaction establishes an address for the contract, enabling subsequent `CallTx` transactions to invoke methods of the contract. Contracts are special accounts that have an associated key-value store, which can be modified by the contract’s methods. Like `SendTx` transactions, `CallTx` transactions have at least one input, which can be used to send tokens to be stored in the contract’s account. Contract methods can in turn send tokens from the contract’s balance to other accounts (either contracts or regular accounts).

To prevent “replay attacks”, in which an attacker could cause a payment to be made twice, each transaction input includes a sequence number known as a *nonce*. An input is valid only if its nonce is one greater than that of the input from that account in the previous transaction that spends from that account.

A transaction enters the network via a `BroadcastTx` RPC call to a node; we call it an *acceptor* node. Each node has a local *mempool* that stores transactions the node has received but has not yet seen included in a committed block. A node validates each transaction before adding it to its mempool. Validation verifies that each of the transaction’s inputs have valid signatures, that its account has sufficient balance, and that the nonce is correct. The balance and nonce validations are performed against the state achieved by applying the acceptor’s mempool transactions to the last committed block the acceptor has seen.

A node receiving a transaction from a peer validates it and appends it to its mempool, as described above. A node has a “peer broadcast” routine for each of its peers, which periodically (every 1ms by default) takes a snapshot of the mempool, and gossips transactions from this snapshot to the peer in the order they appear; preserving this order ensures that nonce values remain in correct sequence.

When a node receives a newly committed block, it removes from its mempool all transactions included in the block and transactions invalidated by the new state (for example, a transaction is removed if its

nonce is no longer correct); it then communicates these changes to each peer broadcast routine to suppress unnecessary late gossiping.

The proposer for a given height and round proposes a prefix of its mempool transactions, in mempool order, thereby preserving correct nonce order of transactions spending from the same account.

2.1 Opportunities to Violate Fairness

Censorship A proposer could pretend it never received a transaction, either directly from the client, or indirectly via gossip.

Order manipulation A correct Tendermint proposer proposes transactions within a block in the local mempool order. Nevertheless, a dishonest proposer could reorder transactions without fear of detection, because that proposer’s mempool order is not externally visible. Indeed, the Tendermint wiki [25] observes that ‘the power to re-order transactions is shared equally among the participants’.

Transaction Injection After receiving a transaction from a peer, a proposer (or its ally) could create another transaction and order it first. For example, a node that has been bribed by an unscrupulous hedge fund might detect that a pension fund has placed a stock order. That node could inject a buy order in front of the pension fund’s, immediately reselling that stock to the pension fund at a markup, a practice known as *front-running*.

3 Design Overview

This section gives an overview of our extensions to the Tendermint protocol; Section 4 presents details.

Ideally, a proposer should not be able to (1) pretend it has not received a transaction that it received, (2) control which received transactions to include in its proposed block, (3) control their order in the block, or (4) inject transactions ahead of those it has received. Any such attempt should preferably result in undeniable proof of misbehavior, and at least produce evidence that can be accumulated and analyzed after-the-fact.

We can make fairness violations much more difficult to achieve without detection by imposing deterministic rules governing the order in which transactions are propagated (making “missing” transactions apparent), which transactions are included in each proposed block, and the order in which they appear. These forms of accountability are achieved by requiring nodes to regularly disclose auditable state information.

Transaction Ingress When a Tendermint node accepts a transaction via a `BROADCASTTx` RPC call, it returns a *receipt* to the caller. We augment this receipt to include *acceptor data*, which includes an *acceptor ID*, a *sequence number*, and an *acceptor signature* that covers both the transaction and the acceptor ID and sequence number. This data gives the caller undeniable proof that the transaction has been accepted into the network; together with additional protocol extensions described below, it also enables detection of certain attempts to censor the transaction or manipulate its ordering. We now concentrate on handling transactions that have been accepted.

Accountable Legitimate Censorship When a node has a legitimate reason for censoring a transaction (for example, it spends from an account on a government blacklist), the node cannot simply drop the transaction. Instead, it explicitly invalidates the transaction by appending signed metadata indicating that this transaction is being censored, perhaps including a justification. The explicitly invalidated transaction is forwarded as usual, and is eventually put in a block and committed to the chain, making the censorship procedure transparent and accountable.

Transaction Propagation Recall that an acceptor validates each transaction against its most recent committed block followed by the earlier uncommitted transactions it has accepted. In contrast to Tendermint, the transaction is *not* validated again during the gossip protocol. Instead, it is validated again only when a proposer includes it in a block (either processed or explicitly rejected). The initial validation ensures that the transaction can execute successfully in at least *some* scenario. The absence of intermediate validation

ensures that a node propagating a transaction has no excuse to drop that transaction, ensuring that every such transaction will eventually reach a proposer. The proposer’s final validation ensures that the sequence of transactions included in its proposed block can execute successfully starting from the state after the previous block.

Tendermint’s mempool serves several purposes: (1) to represent a state against which incoming transactions are validated, (2) to order transactions for gossiping, and (3) to select transactions for proposals. We split the mempool into two distinct pieces to reflect this functionality. An acceptor’s *accepted transaction queue* holds the sequence of transactions it has accepted but have not yet been included in a block. Newly-submitted transactions are validated against the state achieved by starting with the previously committed block and executing each of the transaction’s predecessors in that queue in order. The *outgoing queue* orders transactions for gossip and for inclusion in proposals (Section 4.1.2). This separation supports the above-described modification by allowing an acceptor to validate transactions it accepts only against previous transactions it has accepted, rather than against all gossiped transactions as in Tendermint.

To minimize opportunities for nodes to drop or reorder transactions, we impose the following rule:

Transaction propagation rule When a node accepts a transaction from a client or receives one from a peer, it must send that transaction to each of its peers, unless the transaction has already been included in a committed block. All such transactions must be sent in the same order to each peer, in the same order they were received from each peer, and preserving the acceptor ID order for transactions from the same acceptor. There is one exception: a transaction received from multiple peers should be included in the outgoing order once only, and later duplicates are dropped.

The next section proposes mechanisms for making nodes accountable for following this rule, as well as for transaction selection and ordering in proposals.

4 Detailed Description

This section gives a more detailed account of the changes to Tendermint proposed to enhance accountability for fairness violations. Tendermint already follows the Transaction Propagation Rule presented in the previous section, but there is no mechanism for detecting violations. Furthermore, nodes can easily exclude or reorder transactions without detection. Section 4.1 requires nodes to regularly disclose concise summaries of their outgoing queues, which can subsequently be audited. Moreover, to deny proposers power to select and order transactions, each proposal must include proof that deterministic rules were followed to select transactions from the proposer’s outgoing queue (Section 4.2) and to order them in the proposal (Section 4.3).

4.1 Making Gossip Order Accountable

Detecting violations of the Transaction Propagation Rule requires reliably recording nodes’ internal states and communication states. To address this issue, we propose a novel *one-way accountable channel* mechanism which provides a building block for accountable one-way communication from one node to another.

4.1.1 One-way Accountable Channel (OWAC)

Suppose a sender S sends a sequence of values to a receiver R , which is required to process them in the order sent. Ideally, when S sends a value to R , it would then be able to prove that it had done so, requiring R to process values in the order sent, with no opportunity to examine a message and then pretend not to have received it. Using a classical cryptographic *commitment* protocol [3] would require R to acknowledge a message’s hash before receiving the message itself, but does not solve the problem: R can still pretend not

```

1 Constants
2
3 GracePeriod: integer // max. confirmation "lag"
4 connID: connection ID // to avoid replay attacks
5
6
7
8 Sender S
9
10 ValsSent: array of values
11 lastSent: integer = -1 // last sent index
12 lastConf: integer = -1 // last confirmed index
13 hashCache: integer => hash = {(-1,0)}
14 confirmations: integer => signed message = {}
15 chanR: secure FIFO channel to R
16
17 boolean send(v)
18   if lastSent > lastConf + GracePeriod
19     return false // confirmations too far behind
20   lastSent ++
21   ValsSent[lastSent] = v
22   m = (connID, lastSent, v, lastConf)
23   chanR.send(sign_S(m))
24   return true
25
26 when Receive m = (id, k, confHash, s)
27   if not verifySig(m)
28     claim("invalid signature")
29   if id ≠ connID
30     claim("invalid connection ID")
31   if k ≤ lastConf
32     claim("confirmation out of sequence")
33   if k > lastSent
34     claim("cannot confirm unsent values")
35   j, h = lastConf, hashCache[lastConf]
36   while j < k
37     j ++
38     h = ripemd160(h · ValsSent[j])
39   hashCache[k] = h
40   if confHash ≠ h
41     claim("incorrect hash confirmation")
42   lastConf = k
43   confirmations[lastConf] = m
44 Receiver R
45
46 Msgs: integer => signed message = {}
47 Data: recorded effects of processed messages
48 lastRcvd: integer = -1 // received index
49 lastConf: integer = -1 // last confirmed index
50 lastAckd: integer // last acknowledged index
51 seqHash: hash = 0 // hash of value sequence
52 chanS: secure FIFO channel to S
53
54 when Receive m = (id, i, v, k)
55   if not verifySig(m)
56     claim("invalid signature")
57   if id ≠ connID
58     claim("invalid connection ID")
59   if k < lastAckd
60     claim("acknowledgement out of sequence")
61   if k > lastAckd
62     if k ≠ pendingConfs.removeMin()
63       claim("invalid acknowledgement")
64     lastAckd = k
65   if i > lastRcvd + 1
66     claim("skipped message")
67   if i < lastRcvd + 1
68     if Msgs[i] = m
69       claim("duplicate message")
70     else
71       prove("conflicting messages", m, Msgs[i])
72   lastRcvd = i
73   Msgs[lastRcvd] = m
74   if lastRcvd > lastAckd + GracePeriod
75     prove("too far ahead", Msgs, lastRcvd)
76   if not respectsRules(Msgs, lastRcvd)
77     prove("rules violated", Msgs, lastRcvd)
78   seqHash = ripemd160(seqHash · v)
79   process(Data, v)
80
81 when Event // timer or other event
82   if sendConfPolicy(lastAckd, lastConf, lastRcvd)
83     m = (connID, lastRcvd, seqHash, summary(Data))
84     C.send(sign_R(m))
85     lastConf = lastRcvd
86     pendingConfs.insert(lastRcvd)

```

Figure 1: Protocol in which Sender sends sequence of values to Receiver, and Receiver confirms messages correctly received. Confirmations may lag sends by up to *GracePeriod* messages, but sending does not continue after that unless and until confirmations catch up within *GracePeriod*. Protocol violations detected are reported via `claim` when undeniable proof can't be provided, and `prove` when it can; in the latter case, data on which proof may be based are included as arguments. Each method executes atomically.

to have received a message, even after acknowledging its hash. It would also require an additional round-trip for each message, which is unacceptable in a gossip protocol.

Our goal is a pragmatic design that does not overly burden common-case execution, but that yields proof of deviation when possible, and otherwise yields evidence of possible deviation that can be aggregated over time with other evidence. Detailed pseudocode illustrating the OWAC protocol appears in Figure 1.

The protocol description serves two purposes. First, it *specifies* how correct OWAC implementations can behave. Second, it illustrates how *S* and *R* can detect and react to protocol violations by the other. If one party can prove that the other has violated the protocol, it calls `prove`, with the proof as argument. If one party can detect (but not prove) that the other has violated the protocol, it instead calls `claim`, thereby contributing evidence for potential investigation. Each party logs the messages it receives (Line 43 and Line 73), which can be used to support, defend against, or help evaluate allegations of misbehavior.

Validity rules are modeled by a `respectsRules` method. Similarly, `sendConfPolicy` represents a policy that decides when *R* should confirm messages received since its last confirmation, `process` encapsulates how *R* processes messages, and `summary` produces a concise summary of the result.

For brevity, we elide details such as when historical data can be deleted and what happens after one party accuses the other of violating the protocol.

The key idea behind the OWAC protocol is that each party computes, for each message sent, a cryptographic hash based on that message and prior messages. These hashes are cumulative (the hash for each message is obtained by concatenating the message to the hash of the previous message, and hashing the result; see Lines 38 and 78). In this way, a single hash summarizes the sequence of messages received up to some point. Specifically, *R* sends confirmation of the messages it has received so far, including the hash of the last message received (Lines 83–84). *S* checks that the confirmation contains the correct hash for the messages confirmed (Lines 35–39), thus obtaining proof that *R* has received exactly the messages sent up until that point. *S* records these confirmations in case *R* subsequently denies having received the confirmed messages (Line 43).

At any time (Lines 81–82), *R* can confirm receipt of a *batch* of messages (Lines 83–84), allowing confirmations to be piggybacked onto messages already sent in the host application (here, Tendermint). Each time *S* receives a confirmation, it uses the hash calculated in response to the previous batch of confirmations (Line 35) to calculate and store the hash for this batch (Lines 36–38); this facilitates verification of the next confirmation from *R* (Line 39). Correspondingly, *R* records the highest index of each batch of messages it confirms (Line 86), so it can check that *S* correctly acknowledges its confirmations in order (Lines 59–64).

This batching mechanism allows confirmations from *R* to lag behind messages sent by *S*. To ensure that *R* cannot ignore a message without eventually being detected, *S* allows at most *GracePeriod* messages to be outstanding without confirmation before it refuses to send additional messages (Lines 18–19). If *R* ignores a message, it essentially shuts down that channel, thereby ensuring detection.

In addition to confirming messages received, *R* processes each message (Line 79) and includes with its confirmation a summary of its local data (Line 83), allowing it to prove it has indeed processed all messages received if challenged. Similarly, *S* includes with each message the highest index for which it has received confirmation (Line 22), so that *S* cannot subsequently accuse *R* of failing to confirm messages.

Accusations and Proofs In most cases, when *S* or *R* detects a violation, the proof is self-explanatory. In some cases, one party can detect that the other party violated the protocol, but cannot prove it to a third party. In such cases, that party calls `claim` rather than `prove`. For example, if *S* were to skip a message (perhaps with the intent of accusing *R* of ignoring a message it sent), *R* would detect the omission (Line 65), but would be unable to prove that *S* did not send the skipped message. Nevertheless, *asserting* that the other party has misbehaved adds to a body of evidence that may establish a pattern of misbehavior.

In contrast, in some cases, a protocol violation can be proved. For example, if messages sent by *S* violate application-specific rules encapsulated in `respectsRules`, *R* can produce a proof (because the messages are signed by *S* and cannot be forged). If *S* resends a previous message, *R* cannot prove it, and therefore simply asserts a protocol violation (Line 69). On the other hand, if *S* sends *different* messages for the same index, *R* can prove it did so (Line 71).

We emphasize that the primary purpose of enabling *S* and *R* to monitor one another’s compliance is to discourage noncompliance; therefore violation reports should be rare, especially provable ones.

4.1.2 Using the One-Way Channel in Tendermint

To use the OWAC for gossiping transactions in Tendermint, we instantiate `respectsRules` with a method that performs basic validation of transactions and also ensures that each node propagates transactions from each acceptor in acceptor order, thus preventing nodes from dropping or reordering transactions. Nodes are motivated to verify that transactions received from each of its peers are valid and preserve acceptor order before passing transactions on to their peers; otherwise, they may be blamed for others’ transgressions.

Confirmations are piggybacked on consensus-related messages in Tendermint, in which a node informs its peers each time it enters a new consensus round or changes steps within a round (that is, the “event” that triggers confirmations is when the node is sending a `RoundStep` message anyway).

The `process` method executed upon receiving a transaction from a peer ensures that the transaction is in the node’s outgoing queue. (When a node accepts a transaction from a client, it inserts the transaction into the outgoing queue in the same way after adding acceptor data.) The `summary` method returns a concise

summary of the node’s outgoing queue, along with other information described below, allowing the node to subsequently prove that it indeed has the transaction in its outgoing queue (until the transaction is included in a block). The summary serves two purposes: first, it supports gossip accountability by allowing the node if challenged to prove that it is faithfully following the protocol when gossiping transactions, and second, it allows a proposer to prove that the set of transactions included in its proposed block is consistent with the transaction selection rules discussed in Section 4.2.

Gossip Accountability The summary of the outgoing queue provided by the `summary` method includes transactions received from *all* peers (thus, the `process` and `summary` methods for all incoming OWACs on a node share a common outgoing queue). Furthermore, summaries include the height and hash of the most recently seen committed block, and a sequence number that orders summaries produced by the same node. The implied ordering allows the outgoing queues represented by two summaries to be compared (even if the two summaries were sent to different peers) to verify that the node did not “lose” or reorder transactions in its outgoing queue, and ensuring that consistent information is being sent to all peers.

To support these accountability mechanisms, a node’s outgoing queue is represented as a key-value store implemented using a dynamic Merkle tree [18]. The keys are integers that order transactions in the outgoing queue, and the values are transactions. (Tendermint includes two Merkle tree implementations. The one used for verifying that the parts of a block’s data have been received correctly, as discussed earlier, is for static trees. For the outgoing queue, we use the more sophisticated Merklized AVL+ tree, which supports dynamic inserts and deletes and is used in Tendermint for purposes such as recording accounts and storage.)

Representing the outgoing queue as a Merkle tree allows each node to provide concise summaries of “snapshots” of its outgoing queue at various times, and to prove the accuracy of subsequent responses to requests for more detailed information about the content of the outgoing queue at those times. Section 4.1.3 discusses how this enables accountability mechanisms.

The Merkle tree representation of the outgoing queue supports accountability, but does not efficiently support other outgoing queue operations. For this reason, a node also stores its outgoing queue transactions in additional structures, for internal use only, that do not require the same level of accountability.

Specifically, transactions in the outgoing queue are also stored in order in an array, exactly as in Tendermint’s mempool (see Section 2), except that a transaction that becomes invalid due to the inclusion of another transaction in a newly-committed block is not removed, because it should continue propagating until a block is committed that explicitly rejects the transaction. As in Tendermint, this representation allows peer broadcast routines to efficiently snapshot the outgoing queue, as well as allowing a node to efficiently enumerate transactions to be included in a proposal block.

A local hashmap is also used to map transactions to ordering keys, thereby facilitating duplicate transaction quashing and removal of transactions included in a newly-committed block from the Merkle tree.

4.1.3 Accountability

Who performs accountability checks, how often, and why, are beyond the scope of this paper. Instead, we focus on how the mechanisms described help detect violations of the Transaction Propagation Rule.

As described already, whenever a node confirms a batch of received transactions, it includes the root hash of the Merkle tree representing its outgoing queue. If the node is challenged to prove that a given transaction was included in the outgoing queue as of a certain summary, or even to provide the queue’s entire contents, it can prove the accuracy of its response using standard Merkle proof techniques [18].

A peer can compare the transactions it has sent to a node against such snapshots of the node’s outgoing queue to detect if the node drops or reorders transactions. The block height and hash included in summaries enable confirmation that transactions are dropped only when they are included in a block.

If a node is found to have cheated, say by dropping or reordering transactions in the outgoing queue, the summaries and contents can provide proof that the node has violated the rules. If a node is unwilling or unable to respond to a challenge, it can be penalized using built-in mechanisms such as forfeiting tokens

or being excluded, as well as external mechanisms such as lawsuits, regulatory penalties, and reputational harm. How long a node is required to retain data to facilitate responses to challenges is a policy question.

4.2 Selecting Transactions for a Proposal

The mechanisms that support outgoing queue accountability can also limit proposers' power to select transactions. The Transaction Propagation Rule (Section 3) implies that a node can choose any prefix of its outgoing queue to form a block proposal that satisfies the following constraint: for any transaction in the proposal, all previous transactions from the same acceptor have either already been included in a committed block, or are also included in the proposal.

The length of the proposed prefix is a policy issue. A deterministic rule substantially reduces opportunities for manipulation by proposers. One could choose a constant length, or the longest prefix not exceeding a fixed transaction size total. Relevant parameters could be fixed at creation time (in the ledger's genesis block), adjusted deterministically (like Bitcoin's difficulty level), or adjusted by the ledger's governing body. Deterministic selection makes manipulation such as front running significantly more cumbersome, easier to detect, and easier to assign blame, but does not make it impossible. Stronger, but slightly more intrusive, measures are possible; see Section 5.

To respond to possible future challenges about whether a proposal complies with the deterministic rule, each proposer includes in each proposal its outgoing queue's Merkle root. Even greater accountability can be achieved by requiring verification *before* committing the block.

Tendermint's mechanism for communicating blocks and transactions (see Section 2) can be extended to include a representation of the outgoing queue. Some simple optimizations can largely avoid the increase in bandwidth and storage costs resulting from a naive implementation. First, note that the block need not include the entire contents of the outgoing queue. It suffices to include enough of the outgoing queue to cover all selected transactions, plus additional hashes to enable verification that these transactions indeed form the correct prefix of the outgoing queue.

For example, if only the left subtree leaves were included, we could include a representation of the left subtree that would prove that the selected transactions form an appropriately-sized prefix of the outgoing queue, together with the root hash of the right subtree. This information is enough to verify that the selected transactions were a prefix of the outgoing queue. Here is how to generalize this example. Tendermint's Merkle AVL+ tree has an in-order traversal method that applies a provided function to each node visited. The function returns an indication of whether the traversal should stop. A simple modification of this mechanism allows traversal to continue after enough transactions have been collected, but to refrain from recursing into each new subtree encountered, instead yielding the hash of the subtree's root.

The result is a disclosure of the outgoing queue that suffices to verify that the selected transactions are a prefix of the outgoing queue, and that the Merkle root of the outgoing queue matches the one included in the block header. Tree size is linear in the number of *selected* transactions, and is independent of the total number of transactions in the outgoing queue.

Since only proposal transactions (and not the entire outgoing queue) are included, the partial Merkle tree can replace transactions with their indexes in the block. Validators need not persist the partial Merkle tree after verification.

4.3 Ordering Proposal Transactions

Nodes can control the order in which transactions received from different peers at around the same time are added to their outgoing queues. To avoid abuse of this ability, a proposer is required to reorder transactions in a way that nobody can influence and everyone can verify. Simply randomizing the order could violate dependencies between valid transactions that spend from the same account, resulting in rejection due to incorrect nonce values.

We emphasize that while proposers must preserve the order of transactions that spend from the same account, there is *no* requirement to preserve acceptor order. Acceptor order serves only to ensure that transactions cannot surreptitiously be dropped in transit.

There are many ways to ensure that the order in which transactions are proposed for commitment into the blockchain cannot be unfairly manipulated. Here is one. First, order the transactions in a random order that is beyond anyone’s control and that everyone can verify. A simple and efficient way is to use a pseudo-random number generator (e.g., [15]) seeded using the previous block’s hash XOR’d with the acceptor signature of the first selected transaction. This scheme resists manipulation because no party can control the generator’s seed.

Next, process the transactions in the permutation order, deferring consideration of any transaction that cannot yet be processed because its nonce is out of order. Deferred transactions remain in permutation order. Once all transactions have been considered, the deferred transactions are similarly processed in permutation order, again deferring any transaction that still cannot be processed because its nonce is out of order. This process is repeated until all transactions have been processed, or until a full pass over the deferred transactions yields no more processable transactions. Since there is no way to order the remaining transactions, they can be explicitly rejected.

In principle, this process could take $O(n^2)$ time for n transactions, but such behavior is highly unlikely. It would require the selected and permuted transactions to include a subsequence of $O(n)$ transactions, each of which depends on its successor. So many dependent transactions rarely happen, and it is even more unlikely that a random permutation would produce such an ordering.

5 Discussion

Performance We have not implemented our ideas sufficiently to evaluate their impact on performance. On one hand, they eliminate the need for every transaction to be executed by every node as it propagates through the network. On the other hand, it also adds overhead in various ways. Decentralized ledger technology has the potential to dramatically reduce cost and latency of transactions by eliminating the need for trusted intermediaries that often add days to transaction settlement times. Thus, we should optimize for trust and accountability before focusing on smaller performance improvements.

Resolving Differences We have focused on how to make it difficult to manipulate outcomes without detection, while enabling participants to *explicitly* reject transactions, and perhaps provide a reason, as may be needed to comply with regulations. We have not addressed the question of how a proposer should resolve a transaction’s outcome if it receives the transaction normally from some peers and rejected from others. Another question is whether a transaction could be included by a subsequent proposer after being rejected in an earlier block.

These questions are primarily ledger-specific policy matters, but they also intersect with implementation details. These issues illustrate the benefits of avoiding monolithic designs by structuring systems so that different components can be instantiated differently for different use cases. Tendermint has moved in this direction after the version considered in this paper [27]. We expect that the ideas described here carry over, although we have not yet explored this direction in any detail.

Acceptor Manipulation No amount of tamper-proofing will benefit a transaction that has not been accepted by an acceptor. An acceptor could refuse to accept or even acknowledge a transaction. More subtly, it could attempt to manipulate acceptance order by delaying transactions before assigning an acceptor ID. However, because acceptor order does not affect the final order of transactions included in the same block (see Section 4.3), the acceptor’s only reliable means of influencing transaction order is by significantly delaying transactions. It may be difficult to prove manipulation in individual cases, but repeated patterns of manipulation would emerge from long-term analysis.

Front-running, where a node injects a transaction of its own before another one, is difficult for accep-

tors because they have little control over the eventual relative order of the two transactions; front-running possibilities for proposers are discussed next.

Proposer Manipulation A proposer can reorder transactions it has not yet confirmed. It could also insert transactions accepted by itself or an ally at the end of its outgoing queue. Thus, if the selection policy sometimes allows a proposer to select (almost) its *entire* outgoing queue, then it has some latitude to trial different selections and choose between them after determining the resulting order for each selection (Section 4.3).

To mitigate this possibility, we could further constrain selection. A proposer could be required to exclude transactions accepted by itself, or to order them last. It could also be forbidden from including unconfirmed transactions, or those for which confirmations have not yet been acknowledged. Alternatively or in addition, policies and parameters could be chosen so that, in the common case, selected transactions have already been included in a summary sent to peers and acknowledged, ensuring opportunities for manipulation such as front running are rare and thus more apparent when they do occur.

Permissioned acceptors and proposers suspected of manipulation can be held accountable in various ways in addition to mechanisms that penalize them directly. They may lose business or face regulatory scrutiny or community pressure. If a substantial fraction of acceptors misbehave, trust in the overall network will be diminished, reflecting that the choice of permissioned participants was or has become poor.

Integrating External Decisions Permissioned ledgers aim to take advantage of existing trust and accountability mechanisms, while recognizing that they can never be absolute. We have focused primarily on technical means for making undetectable violation of rules difficult. In some cases, such violations can be proved, allowing for “transactional punishment” without human intervention. For example, Tendermint already allows a node that signs conflicting votes to be automatically penalized via an administrative transaction that confiscates its “stake”; other provable infractions we have enabled can similarly be automatically punished. Nonetheless, some violations, including acceptor manipulation, can be punished only based on judgments made outside the system (informed by evidence produced by the system).

This raises the question of what can be done when such external judgments are made. Again, this is a policy matter that intersects with technical details. For example, the rules governing a given ledger might enable a majority of participants to impose a penalty on one party, or, say five out of seven members of a governance board to permanently exclude the party that is judged to be behaving dishonestly.

No technical solution can prevent or solve all human disagreements, but by making the ledger’s rules precise, and violations detectable, many disagreements might be avoided in the first place, and mechanisms that support effective governance can facilitate resolution even when human intervention is needed.

Legitimate Losses As described so far, transactions could be lost through no malicious intent. An acceptor might crash immediately after sending a response and before sending the transaction to its peers. Should it be held responsible for the loss of the transaction in this case and if so how?

If transaction loss is sufficiently undesirable, an acceptor may be heavily penalized for such a loss, giving it an incentive to ensure this does not happen. It could do so by persisting the transaction before sending the receipt, which would add significant overhead using traditional storage technologies. As nonvolatile RAM [17] becomes cheaper and more widely available, avoiding such losses will impose less overhead, thus reducing the level of penalties needed to encourage avoiding it.

Fault-Tolerance As described, our changes make the protocol susceptible to failures, such as a node crashing and missing messages. To resume normal operation, a restarting node can report the outage via administrative transactions; downstream nodes may forgive the omissions, which are made visible and accountable by the administrative messages. If a node omits a transaction without explanation, its peer may insert an administrative transaction to report the omission and continue normal operation. Either way, evidence is created to shed light on the reason for the omission.

6 Related work

To our knowledge, the blockchain-related work most closely related to ours is Factom [23], a “proof of publication” system that aggregates “entries” submitted to “federated servers” and records hashes in the Bitcoin ledger to support undeniable proof of the entries’ existence at a certain time. Factom’s approach to preventing manipulation is similar in spirit to ours. For example, Factom servers produce “confirmations” of entries that are ordered, and ensures that servers cannot “lose” them or manipulate their order without detection. It also incorporates mechanisms for proving violations of the rules and penalizing the culprits automatically, as well as for allowing the “community” to remove a server if it loses support for any reason.

Factom allows clients to buy “entry credits” (using tokens called “factoids”), which reserve the right to submit an entry, without revealing identity or content. Instead, a hash of the entry is included, allowing clients to reveal the original content after the entry has already been included in the ledger.

Similar techniques could be used with our system to acquire acknowledgment of an intended transaction from an acceptor before revealing the transaction. However, a key difference for our context is that the semantics of transactions and smart contracts depend on ordering; thus to guarantee ordering to a transaction without being able to process it requires a fundamentally different approach.

It might seem that projects such as Enigma [29] and Hawk [12]—which entail techniques for processing transactions without knowing their contents—might provide an alternative way to achieve similar accountability benefits while supporting transactions. However, such approaches do not preclude the possibility of validators favoring transactions of their allies, because they can identify the transactions with help from their allies, even though the transactions may be encrypted (in part).

Techniques used by our OWAC protocol—as well as for representing nodes’ outgoing queues—are reminiscent of previous work (e.g., [1, 13, 16, 18, 19]) in which new data includes hashes of previous data, thus preventing tampering, and cryptographic signatures are used to authenticate data, thus preventing forgery.

We have explored the use of such techniques specifically for enhancing accountability in distributed ledgers. Previous work has addressed accountability in distributed systems more generally. Yumerefendi and Chase [28] propose that accountability be considered a “first-class design principle” for dependable network systems. The design principles espoused in this paper are consistent with that vision.

Reiter and Birman [21] identify attacks that can cause honest servers to misbehave by violating causality when delivering messages, citing front-running as an example. They propose a solution based on threshold cryptography, whereby honest servers participate in decrypting messages only after committing to deliver them. Cachin et al. [4] present efficiency enhancements and more formal analysis. These approaches assume an underlying atomic broadcast protocol, and thus inherit their assumptions and overhead in addition to their guarantees. Our approach is lightweight and more flexible: we do not attempt to ensure all transactions are delivered to all participants in the same order. Instead, we impose rules for ensuring that the orders in which transactions are propagated and included in blocks are not manipulated, and propose mechanisms that discourage accountable entities from violating these rules by detecting (potential) violations and holding perpetrators accountable.

Haeberlen et al. [9, 10] similarly aim for lightweight approaches that focus on detecting misbehavior in ways that perpetrators can be held accountable, rather than on preventing or masking it. Our work is similar to theirs in that participants are required to maintain authenticated, tamper-proof records that can be examined by others to detect misbehavior. Some of the techniques we propose are reminiscent of optimizations used by Haeberlen et al., including buffering logs before sending, and allowing participants to prove claims about data without exchanging entire data structures.

Our work also differs in several ways. Haeberlen et al. propose protocols that aim to always eventually detect a byzantine participant while never falsely accusing an honest one, addressing questions such as when participants should challenge each other and how they should respond. In contrast, we have described mechanisms for proving misbehavior in some cases and exposing evidence that may be accumulated and interpreted externally in others, while not addressing how this should be done.

Haeberlen et al. propose a general methodology in which correct behavior of each participant is defined

by a deterministic state machine, and is held accountable for following its transitions faithfully according to messages received. In contrast, our work specifically addresses integration into a permissioned distributed ledger context, exemplified by Tendermint.

Neither our ideas nor those of Haeberlen et al. can prevent a participant from manipulating the order in which concurrent messages are received from different peers. However, our work includes mechanisms that severely limit the ability of participants to exploit such manipulation. In particular, we ensure that validators cannot control the ordering of transactions within a block even if they manipulate the order in which they claim to receive them.

We also introduce the idea of accountable censorship, which is an application-level issue that is not addressed by a generic approach to state machine logging for an existing application.

7 Concluding remarks

Designing distributed ledgers to be resistant to internal fairness violations is a complex and important problem, and this paper is only a first step. We exploit the common-sense observation that permissioned ledgers, which have recourse to real-world measures such as fines, expulsions, or legal action, can rely on unobtrusive, after-the-fact auditing and statistical analysis to detect and deter misbehavior, especially repeated misbehavior. By reducing the number of non-deterministic choices, auditors have fewer possibilities to consider when anomalies are detected. To this end, we have proposed several deterministic mechanisms intended to make violations more cumbersome and easier to detect. There are many directions for future work. Can we devise more rigorous, more lightweight mechanisms? What other kinds of fairness violations need to be deterred? Are there theoretical bounds on the kinds of fairness properties that can be monitored, and the cost of such monitoring?

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