NimbleChain: Low-latency consensusless cryptocurrencies in general-purpose permissionless blockchains

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Abstract—Nakamoto's seminal work gave rise to permissionless blockchains – as well as a wide range of proposals to mitigate its performance shortcomings. Despite substantial throughput and energy efficiency achievements, most proposals only bring modest (or marginal) gains in transaction commit latency. Consequently, commit latencies in today's permissionless blockchain landscape remain prohibitively high for latency-sensitive geo-distributed applications.

This paper proposes NimbleChain, which extends standard permissionless blockchains with a fast path that delivers consensusless promises of commitment. This fast path supports cryptocurrency transactions and only takes a small fraction of the original commit latency, while providing consistency guarantees that are strong enough to ensure correct cryptocurrencies. Since today's general-purpose blockchains also support smart contract transactions, which typically have (strong) sequential consistency needs, NimbleChain implements a hybrid consistency model that also supports strongly-consistent applications. To the best of our knowledge, NimbleChain is the first system to bring together fast consensusless transactions with strongly-consistent consensus-based transactions in a permissionless setting.

We implement NimbleChain as an extension of Ethereum and evaluate it in a 500-node geo-distributed deployment. The results show that the average latency to promise a transaction is an order of magnitude faster than consensus-based commit, with minimal overhead when compared with a vanilla Ethereum implementation.

Index Terms—Distributed systems, permissionless blockchains, cryptocurrencies, smart contracts, hybrid consistency

1 INTRODUCTION

The majority of permissionless blockchains, including mainstream ones such as Bitcoin [45] or Ethereum [61], rely on the foundations of Nakamoto's seminal consensus protocol [45]. In these systems, the probability that a given block has stabilized grows with the number of blocks that succeed it in the chain. Hence, by setting a high enough threshold to consider a block – and the transactions therein – as committed, one can ensure an arbitrarily low probability of the block being discarded. This is commonly known as finality and has been formalized as a persistence property by Garay et al. [17].

Permissionless blockchains can thereby be used as a (probabilistic) total-order broadcast service with unique features, in particular their resilience to Sybil attacks which characterize permissionless environments. Permissionless blockchains support a wide range of geo-distributed applications, from cryptocurrencies to general-purpose smart contracts, but unfortunately they are also known for their poor performance.

In recent years, the research community has contributed with important improvements to permissionless blockchains – from improvements of Nakamoto's longest chain rule [58], [61], [33], [57], [55], hierarchical and parallel chains [16], [48], [62], [4], sharded blockchains [53], [32], [63], [14], Layer-2 approaches [52], [23], [41], [11], [24], BFT-based blockchains [31], [49], [11], [19], [44], [87], and Proof-of-X alternatives [28], [64], [19], [3], [12], [2], [8]. These approaches have focused mostly on improvements to throughput and/or energy efficiency, bringing only modest improvements to commit latency. Some notable exceptions reduce commit latencies by sacrificing security or scalability (as we discuss in §8). In fact, as of today, commit latencies remain notably high in mainstream permissionless blockchains – around 1 hour in Bitcoin and 3 minutes in Ethereum.

Such high commit latencies are especially prohibitive for many applications that require low-latency transactions. Examples range from merchant applications that need to deliver goods quickly (< 30 seconds) [27], such as point-of-sale purchases and retail vending machines, take-away stores, online shopping, supermarket checkouts and bike sharing systems [10], [27], [5], [22], to blockchain-backed IoT devices and applications [23]. To overcome the high commit delays, merchants and service providers frequently adopt risky 0- or 1-confirmation policies [10], which accept transactions as granted well before the underlying blockchain can provide sufficiently strong guarantees of their persistence. Such policies are inherently vulnerable to double-spending attacks.

The commit latencies of mainstream permissionless blockchains reflect two well-known limitations of Nakamoto's consensus protocol: for the sake of correctness, blocks need to be generated (on average) at a slow pace with respect to network latency, and a transaction should
only be considered as committed (i.e., persistent) after it is followed by a long sequence of (slowly generated) blocks in the chain \cite{17}. To further complicate matters, a recent study \cite{54} concluded that, due to the emergence of powerful mining pools, blockchain systems should wait for even larger blockchain suffixes before committing, which means that commit latency is bound to increase, rather than decrease.

This paper focuses on improving the latency of general-purpose permissionless blockchains. Our work is inspired by recent results by Guerraoui et al. \cite{21}, which have proved that the actual consistency needs of a cryptocurrency can be satisfied without resorting to consensus.

As a first contribution, we propose an extension to the traditional issue/commit model, by introducing the notion of promise of commitment, or simply promise. A promise is a new event in a transaction's life cycle. Informally, when a process promises a transaction \( t \), that means that \( t \) will be eventually committed by every correct process, even if \( t \) is part of a double-spending attempt by a malicious user, while satisfying any causal dependencies of \( t \). Hence, the promise event captures weaker consistency guarantees than the commit event, as different processes may promise transactions in different orders (i.e., the promise event is not totally ordered). Still, the guarantees of the promise event are strong enough to fulfil the consistency needs of cryptocurrencies and other applications.

To be effectively advantageous, a system implementing the novel issue/promise/commit model should ensure that, for most transactions, a large portion of correct processes (if not all) actually promise such transactions much earlier than they commit them.

As a second contribution, we address the above goal by proposing NimbleChain. NimbleChain extends permissionless blockchains based on the Bitcoin Backbone Protocol (BBP) \cite{17} with a consensusless promise fast path. This fast path allows cryptocurrency transactions, which constitute the bulk of today’s most important permissionless blockchains (i.e., almost 100% in Bitcoin \cite{5} and 44% in Ethereum \cite{54}), to be promised substantially faster than the original commit, in a large portion of correct processes. Since today’s general-purpose blockchains also support smart contract transactions, which typically have (strong) sequential consistency needs, NimbleChain implements a hybrid consistency model that supports both types of transactions. To the best of our knowledge, NimbleChain is the first system to bring together fast consensusless transactions with strongly-consistent consensus-based transactions in a permissionless setting.

As a third contribution, we implement NimbleChain as an extension of the Ethereum blockchain, which demonstrates the practicality of our proposal. Furthermore, we show that NimbleChain can also extend most recent proposals for high-throughput and mid-latency blockchains, which are still built on Nakamoto’s consensus foundations.

As a final contribution, an evaluation with 500 processes in a realistic geo-distributed environment that shows that NimbleChain’s consensusless fast path reduce the commit latencies of cryptocurrency transactions by an order of magnitude with negligible overhead when compared with Ethereum.

The rest of the paper is organized as follows. \cite{2} provides background on permissionless blockchains and describes a generic baseline protocol. \cite{4} presents NimbleChain, which extends the baseline with consensusless transactions. \cite{5} describes how we can leverage NimbleChain’s promises to implement low-latency cryptocurrencies. \cite{6} evaluates our implementation of NimbleChain as an extension of Ethereum in a large-scale geo-distributed scenario. \cite{7} discusses the limitations of NimbleChain. \cite{8} surveys related work. \cite{9} concludes the paper.

1 Background

In this work, we consider the BBP as our starting point, which we will extend in the following sections.

2.1 Assumptions.

The BBP runs on a peer-to-peer network of processes and relies on the following assumptions \cite{17, 27, 50, 28}. First, Byzantine adversaries control less than 50% of the total mining power that is used to produce blocks and do not have computational power to subvert the standard cryptographic primitives. Any message broadcast by a correct process is delivered to every correct process with high probability, and with a maximum delay of \( D \) \cite{50, 47, 53, 28}. This is often a hidden assumption of permissionless blockchains systems but it is in fact a critical aspect of the system that we do not only expose but embrace. In fact, in Nakamoto consensus the difficulty of the Proof-of-Work (PoW) puzzle is based on the maximum delivery delay \( D \) \cite{47, 53}, and hence this is an assumption shared by Bitcoin and Ethereum. The same applies to proof-of-stake blockchains such as Ouroboros \cite{28} and Algorand \cite{19} which assume a bounded delay. The correctness of BBP, and systems such as Bitcoin or Ethereum, thus depends on the premise that the system takes much longer to generate a new block than to propagate it \cite{17}. Let us denote \( B \) as the overall average block generation time. Hence, we assume that \( r = D/B \) is relatively small \cite{17}.

For presentation simplicity, we assume that all processes can produce blocks. Moreover, we also assume that each correct client is collocated with a correct processes participating in the protocol. Devising robust solutions to support correct
clients that interact with possibly Byzantine processes running the protocol is an open problem, which is orthogonal to our work.\footnote{For presentation simplicity, we present a formulation that is simpler than Garay et al.’s original one. Namely, we omit some parameters that are orthogonal to our contributions in this paper, and explicitly use the term commit.}

A transaction is signed by the process that issues it. The body of a transaction is an application-dependent payload (e.g. the target account and amount to transfer in a cryptocurrency transaction, or, in a smart contract transaction, the target smart contract, its method and arguments). Each transaction also carries a local sequence number, which is consecutively unique for that issuer. Note that a Byzantine transaction also carries a local sequence number, which is greater than Garay et al.’s original one. Namely, we omit some parameters as a cryptographically linked list of blocks. Blocks have a monotonically increasing gap-free sequence number and each block includes a totally-ordered sequence of transactions. The mempool is a local queue of individual transactions not yet included in the local chain. The transactions in the mempool are ordered after the transactions in the chain. When receiving a transaction, a process performs a series of validations such as checking for funds, checking whether another transaction with the same identifier already exists in the local ledger (i.e. a double-spend attempt) and verifying the transaction’s digital signature, among others. If the transaction is valid and not yet in the local chain, it is inserted in the mempool.

Processes initially share the same genesis block $b_0$ and produce blocks by selecting a subset of transactions in the mempool and creating a proof that depends on these transactions and on the last block in the local chain. The proof is a Sybil-proof leader election mechanism, such as PoW, that ensures the process legally produced the block. The puzzle difficulty of PoW is a function of $D$\footnote{We start by defining the event of committing a transaction as follows. If a correct process $p$ has a block $b$ in its blockchain followed by at least $C$ other blocks, we say that every transaction included in $b$ is committed at $p$. Garay et al.\cite{Garay} proved that BBP ensures the two key properties below associated with the commit event, with high probability$^{[1]}$.}

Persistence: If process $p$ commits a block $b$, and consequently the transactions in $b$, then any correct process has block $b$ in the same position in the blockchain, from this moment on.

Liveness: if a correct process submits a transaction $t$ then all correct process eventually commit $t$.

Two important corollaries can be easily drawn from the above properties. The first one is that, if a correct process $p$ commits a transaction $t$, then all other correct processes will eventually commit $t$. A second corollary is that, if a correct process $p$ commits transaction $t_A$ and, later, transaction $t_B$, then any other correct process $q$ will commit both transactions in the same order – in other words, the commit event is totally ordered.

Together, the above properties and the associated corollaries constitute strong consistency guarantees, which BBP provides with high probability. These enable many geo-distributed applications to operate even when operating under an adversarial permissionless environment. For instance, state-machine replication can be built on top of BBP through smart contracts. Yet, these guarantees are provided at the cost of a high latency.

2.2 Properties.

Our work hinges on the observation, previously identified by Guerraoui et al.\cite{Guerraoui}, that cryptocurrency transactions, also known as asset transfer transactions, do not need consensus. The intuition behind this observation is the following. In an asset transfer scenario, the system maintains a set of accounts where each account maintains the number of assets held, for instance the amount of Bitcoins in a given account. Each account has a single owner that can withdraw funds from this account and transfer them to other accounts. The other users in the system can only read the accounts balance and transfer funds to it (from their own accounts). Therefore, it is the sole responsibility of the account owner to order the withdrawal transactions. Intuitively, this removes the need for consensus and the account owner does not need to coordinate with any other process in the system (i.e. formally such system can be used to implement a sequential object type of consensus number of 1 in Herlihy’s hierarchy\footnote{We refer the reader to the work of Guerraoui et al. for a formal description and proof of this observation\cite{Guerraoui}.}). Note however that permissionless blockchains also serve transactions issued by other applications with strong consistency requirements, such as those issued to/by smart contracts, which do require consensus. We describe in the next sections how NimbleChain combines these different transaction types in an hybrid consistency model.

2.3 BBP Algorithm.

At a high-level, the BBP algorithm works as follows. Each process holds a local ledger of transactions that consolidates two components: a local copy of the blockchain (or, simply, local chain) and the mempool. The local chain is organized as a cryptographically linked list of blocks. Blocks have a monotonically increasing gap-free sequence number and
3 Promise of Commitment

NimbleChain extends the life-cycle of a transaction, \( t \), with an additional event, a promise of commitment of \( t \), which we abbreviate to promise of \( t \).

The main motivation behind the promise event is that many applications, such as cryptocurrencies, do not need the strong, total order guarantees provided by the (slow) commit event. Instead, the semantics of such applications only require weaker consistency guarantees, which the promise event delivers. Next, we first provide the intuition behind the promise event and later formally formulate the corresponding properties.

We start by informally presenting the first guarantee associated with the promise event. Whenever a process \( p \) is able to anticipate – through some means, as we discuss later on – that correct processes will eventually commit \( t \), \( p \) can expose such a priori guarantee by promising \( t \). For applications that do not require a total order, the promise event allows them to continue their processing without waiting for slow-paced (consensus-based) commit to determine the final order where \( t \) will be placed in the (totally ordered) distributed ledger. Naturally, the earlier a process \( p \) promises \( t \) (relatively to the instant when \( p \) commits \( t \)), the higher the above benefit will be.

Note that, when a process is not able to safely anticipate the promise of \( t \), it can simply promise \( t \) when it is about to commit \( t \). However, this behaviour brings no benefit, so it is desirable that a process only rarely resorts to this case.

One important corollary is that the above guarantee associated with the promise event is strong enough to resist double-spend attempts. More precisely, suppose a byzantine process issues two conflicting transactions, \( t' \) and \( t'' \) in an attempt to double-spend. Recall that the power of BBP ensures that, if one of such transactions, say \( t' \), commits, then the other(s) conflicting transaction(s) will not. Hence, if a correct process promises \( t' \), then that process can immediately infer that, even if the issuer of \( t' \) maliciously tried to double-spend, correct processes will choose \( t' \) as the one to commit and, thus, discard any conflicting transactions.

While the above guarantees of the promise event may seem appealing, they are too weak for applications whose semantics entail causal dependencies across transactions. For instance, let us consider a correct process \( p_1 \), that commits a transaction \( t_1 \), issued by some other process. Based on the effects of \( t_1 \), \( p_1 \) decides to issue \( t_2 \). Therefore, \( t_2 \) causally depends on \( t_1 \). Since \( t_2 \) is issued by a correct process, the liveness property of BBP ensures that \( t_2 \) will eventually commit (on every correct process) after \( t_1 \) has committed. In other words, both transactions will commit in causal order at every correct process. It is easy to generalize this example and prove that, as long as new transactions are issued (at some correct process) after their causal dependencies have committed (at the same process), then BBP implicitly ensures causal order.

When we introduce the promise event to the transaction’s life-cycle, it becomes desirable to allow processes to issue new transactions as soon as their causal dependencies have been promised – since this will translate to latency improvements. However, it is important that this change does not threaten causal order guarantees on which many applications rely. To illustrate, consider that \( p_1 \) observes that \( t_1 \) (issued by some other process) has been promised, and, consequently, decides to issue \( t_2 \). Note that at this point, \( t_1 \) and \( t_2 \) may not yet have committed anywhere. Moreover, correct processes other that \( p_1 \) may not even have promised \( t_1 \). Intuitively, anomalies such as a correct process later promising or committing \( t_2 \) and \( t_1 \) in this order (i.e., violating causal order) should not be allowed.

Finally, we can capture the above informal guarantees by formulating the following properties.

Eventually committed upon promised: if a correct process promises a transaction \( t \) then all correct process eventually commit \( t \).

Causal order: if a correct process promises (resp., commits) a transaction \( t \) then that process has already promised (resp., committed) every transaction on which \( t \) causally depends.

In the latter, we assume that transactions carry a metadata field that denotes its causal dependencies (using some suitable causality tracking mechanism). Further, the causal dependencies of a transaction \( t \) issued by correct process \( p \) observe the following:

- they must include every transaction that \( p \) has previously issued;
- they may optionally include transactions issued by processes other than \( p \), under the condition that they have already been promised by \( p \) when \( p \) issues \( t \).

Finally, we remark that, in general-purpose blockchains, different applications or different operations of a given application, might have distinct consistency demands. This explains why we decided to add the promise event to the original issue/commit model, rather than simply replacing the commit event with the promise event. The richer issue/promise/commit event set offers a hybrid consistency model. It allows different applications, or different operations from the same application, to choose whether to wait for a transaction to be promised or committed, depending on the required guarantees.

4 NimbleChain

In this section we present NimbleChain’s algorithm and correctness arguments. §4.1 describes the main insight behind NimbleChain and an overview of its main components. §4.2 then details the main algorithm of NimbleChain. §4.3 discusses how NimbleChain can be tuned to maximize its resilience. Finally, §4.4 details how NimbleChain enforces causal order and §4.5 presents NimbleChain’s correctness arguments.

4.1 Insight and overview

As discussed in §2, BBP offers a predictable outcome for correctly issued transactions – eventually they are guaranteed to commit. However, when it comes to double-spending
transactions, the outcome is unpredictable – from a set of double-spending transactions, \{t, t', ...\}, the protocol will non-deterministically select one transaction to commit and discard the remaining ones. For this reason, if a process \( p \) wishes to know whether some transaction \( t \), issued by another process, will eventually commit, \( p \) needs to wait for the slow consensus-based BPP to agree on a decision regarding \( t \).

The main goal of NimbleChain is to enable processes to correctly anticipate, well ahead in time, for which transactions the (eventual) decision of BPP will be to commit them. Whenever a process \( p \) is able to anticipate that with high probability for some transaction \( t \), \( p \) can immediately promise \( t \).

Before explaining how NimbleChain achieves this goal, let us start by discussing a straw man proposal. In the following, for a given transaction \( t \), we denote by \( C(t) \) the set of transactions with the same identifier (issuer, sequence number) as \( t \). By definition, \( C(t) \) always has a single element if a correct process issued \( t \); otherwise, \( C(t) \) may have additional transactions, which conflict with each other and represent a double-spending attempt.

We can now sketch the following straw man proposal. Whenever a correct process \( p \) receives some transaction \( t \), \( p \) executes the three steps below:

1) Selection: \( p \) proposes \( t \) to every other correct process and waits until the system agrees (by some means) on pre-selecting some transaction \( t_{\text{selected}} \) from \( C(t) \) (note that, if \( t \) is issued by a correct process, \( t_{\text{selected}} = t \));
2) Promise: \( p \) promises \( t_{\text{selected}} \);
3) Deterministic commit: finally, enforce BPP to commit the selected transaction, \( t_{\text{selected}} \).

To ensure step 3, correct processes engage in a coordinated effort that we hereafter designate as deterministic BPP commit. Concretely, a deterministic BPP commit of some transaction \( t_{\text{selected}} \) is accomplished by having every correct process reject: (i) the inclusion of any transaction that conflicts with \( t_{\text{selected}} \) in their mempools; and (ii) any chain that contains any transaction that conflicts with \( t_{\text{selected}} \).

It is easy to show that these rejection conditions effectively eliminate the non-determinism of the BPP when handling double-spending transactions (when \( C(t_{\text{selected}}) \) has more transactions than \( t_{\text{selected}} \)). Concretely, such conditions ensure that the whole mining power of correct processes will be used towards appending the pre-selected transaction, \( t_{\text{selected}} \), to their chains and continuing building on a chain with \( t_{\text{selected}} \) (without replacing the chain containing \( t_{\text{selected}} \) with alternative chains with a conflicting transaction) until \( t_{\text{selected}} \) is eventually followed by enough blocks to commit (in the same way as with transactions issued by correct processes).

However, the selection step (1) of this approach implicitly requires solving consensus, which is precisely what BPP achieves. Hence, anticipating one consensus protocol with another one does not suggest any tangible advantage.

The design of NimbleChain is inspired by the high-level recipe of this straw man proposal. We introduce fundamental adaptations to the above recipe to reach a practical and effective approach.

In a nutshell, NimbleChain handles transactions according to two parallel paths, which we call the fast and slow paths. Transactions are handled in each path through distinct protocols and NimbleChain consolidates their outcomes to ensure they reach consistent decisions. These paths relate to the straw man proposal as follows: the selection step (1) is replaced by NimbleChain’s fast path, and the deterministic BPP commit step (3) by NimbleChain’s slow path.

At the core of this adaptation lies a fundamental disruption: the selection stage – as implemented by NimbleChain’s fast path – no longer resorts to consensus. More precisely, the fast path promises transactions through a lightweight consensusless ageing-based protocol. This protocol is best-effort by nature, in the sense that, in worst-case scenarios, one or more correct processes \( p_{\text{decided}} \) may not be able to promise in the fast path. As we explain next, such scenarios only arise due to double-spend transactions.

The key insight of NimbleChain is that, if at least one correct process \( p_{\text{decided}} \) promises a transaction \( t_{\text{selected}} \), then every correct process \( p_{\text{decided}} \) will actively contribute to the deterministic BPP commit of \( t_{\text{selected}} \) (instead of any transaction conflicting with \( t_{\text{selected}} \)). Therefore, the full set of correct processes engages in the deterministic BPP commit of \( t_{\text{selected}} \). This ensures that, with high probability, BPP will eventually commit \( t \) and, hence, even \( p_{\text{decided}} \) will later promise/commit \( t_{\text{selected}} \).

From the perspective of a process \( p \), the life cycle of a transaction \( t \) can follow one out of the scenarios that Figure 1 depicts:

- Process \( p \) may promise \( t \) first via the fast path and, later, commit \( t \) via the slow path (Figure 1 top).
- Alternatively, \( p \) may not be able to reach a fast-path decision for \( t \) and, later, the slow path commits \( t \) – this means that \( t \) is simultaneously promised and committed (Figure 1 bottom).
- Finally, \( p \) may decide to not promise \( t \) in the fast path and, subsequently, the slow path decides to not commit \( t \) (for being part of a double-spend attempt), which implies that \( t \) is discarded (in other words, the process decides to neither promise nor commit \( t \)).

Table 1 summarizes the essential differences between both paths.

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**Table 1:** Differences Between Fast and Slow Paths

| Path               | Slow Path (Bitcoin Backbone Protocol) | Fast Path |
|--------------------|--------------------------------------|-----------|
| Provides           | Time                                 | No time   |
| Receives           | t                                     | t         |
| Promises           | t                                     | t, t'     |
| Commits            | t                                     | t         |
| Selection          | t_{\text{selected}}                   | t_{\text{selected}} |
| Promise            | t_{\text{selected}}                   | t_{\text{selected}} |
| Deterministic Commit| t_{\text{selected}}                   | t_{\text{selected}} |

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Fig. 1: Transaction life cycles in NimbleChain.
### 4.2 Main algorithm

We now present the main algorithm of NimbleChain, which materializes the insight described previously. For presentation simplicity, we here assume that transactions have no causal dependencies, hence different correct processes are free to commit them in arbitrary orders. We lift this simplification in §4.4.

In NimbleChain, the state maintained by each process corresponds to BBP state (namely, a local chain and a mempool), plus extra metadata for each transaction as depicted in Figure 2. Next, we detail the algorithms of the main components of NimbleChain, its fast and slow paths.

**Fast path: transaction ageing.** The fast path protocol consists of the ageing protocol in Algorithm 1 which leverages the a-priori knowledge of a maximum propagation delay $D$.

When receiving a transaction $t$, a process $p$ assigns to $t$ a timestamp based on $p$’s local clock. From that instant on, we say that $t$ is *aging* (ln. 14). We denote by $age_p(t)$ the age of a transaction $t$ at process $p$. Its value is determined by function $age$ in Algorithm 1 depending on whether $t$ is already aged (ln. 7), still ageing (ln. 10) or in none of such states (ln. 12).

Initially, $age_p(t) = \perp$. Once a transaction starts ageing, its age is measured in units of $D$. We also define a system-wide parameter $ageing$ threshold (AT). AT has a minimum value of 4 but it can assume other values, which provide a trade-off between latency and resiliency which we analyze in further detail in §4.3. For presentation simplicity, this section assumes $AT = 4$.

If $t$ ages up to $AT$ without $p$ receiving any double-spend of $t$, we say that $t$ has *successfully aged* at $p$. As a result, $p$ promises $t$ (ln. 19). As an important corollary, transactions issued by correct processes (which, by definition, do not have double-spend) will always successfully age and hence be promised in the fast path at every correct process. As we discuss in §4.3 causal dependencies may introduce some exceptions to this corollary.

If, otherwise, $p$ receives a transaction $t'$ that conflicts with $t$ before $p$ has promised $t$, $p$ stops the ageing of $t$ and registers for how long $t$ had already aged, i.e., $age_p(t)$ is frozen at such value, see ln. 28. In this case, the fast path has not been able to promise $t$. Therefore, $p$ needs to wait for the eventual commit or discard of $t$ through BBP’s slow path.

![Fig. 2: Local state of a process in NimbleChain.](image)

#### Algorithm 1: Ageing protocol (NimbleChain’s fast path)

1. **Initially**
   
   - $ageingTxs \leftarrow \emptyset$;
   - $agedTxs \leftarrow \emptyset$;

2. **Function $age$ (transaction $t$):**
   
   - $(t_{previous}, age) \leftarrow lookup(agedTxs, t.issuer, t.seqno)$;
   - if $t_{previous} \neq \emptyset$ then
     - return $age$;
   - $(t_{previous}, receivedtime) \leftarrow lookup(ageingTxs, t.issuer, t.seqno)$;
   - if $t_{previous} \neq \emptyset$ then
     - return now $-$ receivedtime;
   - else
     - return $\perp$;

3. **Procedure $AgeingMonitor$:**
   
   - while true do
     - for each $(t, receivedtime)$ in $ageingTxs$ do
       - if now $-$ received $= AT$ then
         - remove($ageingTxs$, $t$);
         - add($agedTxs$, $t$, $AT$);
       - else
         - return $\perp$;
     
   
   - Upon receiving transaction $t$:
     
     - $t_{previous} \leftarrow lookup(agedTxs \cup ageingTxs, t.issuer, t.seqno)$;
     - if $t_{previous} = \emptyset$ then
       - add($ageingTxs$, $t$, now);
     - else
       - if $t_{previous} \neq t$ then
         - reject $t$ from mempool;
         - $(t_{previous}, receivedtime) \leftarrow lookup(ageingTxs, t.issuer, t.seqno)$;
         - if $t_{previous} \neq \emptyset$ then
           - remove($ageingTxs$, $t_{previous}$);
           - add($agedTxs$, $t$, now $-$ receivedtime));

Further, since $t'$ was received when $p$ was already ageing a conflicting transaction ($t$), $p$ rejects $t'$ from its mempool (ln. 26) and, furthermore, does not age $t'$. Therefore, $age_p(t')$ remains $\perp$. Consequently, when multiple transactions conflict, a correct process $p$ will only age one of them (either successfully or not), i.e., the first transaction that $p$ received among multiple conflicting transactions.

Figure 3 illustrates both scenarios, the successful and unsuccessful ageing of a transaction. Most transactions successfully age (thus are promised via the fast path) before...
reaching the local committed chain. Transactions issued by malicious processes that are part of a double-spend may have their ageing stopped, and their outcome will only be eventually decided by BBP’s slow path.

It is worth noting that, since transactions are delivered at different times at distinct processes, their ageing state is not guaranteed to be consistent across the system. Figure 3 illustrates some possible inconsistencies. It may occur that t successfully ages (thus, is promised in the fast path) in some processes (within an interval of D), but does not in others. Further, in those processes where t does not age successfully, its age may be fixed at different values (at distinct processes). Still, since the behaviour of the broadcast layer is bounded by a maximum delivery delay (D), the following lemma is satisfied.

**Lemma 1.** If a correct process \( p \) successfully ages a transaction \( t \) (i.e., \( \text{age}_p(t) = AT \)) then, with high probability: (1) for any correct process \( q \), \( \text{age}_q(t) \neq \perp \) and \( \text{age}_q(t) \geq AT - 2 \); further, (2) for any transaction \( t' \) that conflicts with \( t \), then \( \text{age}_q(t') = \perp \) for every correct process \( q \).

**Proof.** (1) Suppose, by contradiction, that either (a) \( \text{age}_q(t) < AT - 2 \) or (b) \( \text{age}_q(t) = \perp \); this implies that either (a) \( q \) received \( t' \) either less than \( 2D \) after \( q \) first received \( t \), or (b) that \( q \) received \( t' \) before \( t \), respectively. It is easy to show that, since \( p \) received \( t \) and \( t' \) more than \( 4D \) after (since \( \text{age}_p(t) = AT \)), hypothesis (a) and (b) only occur in executions where \( t \) or \( t' \) were delivered at \( q \) or \( p \) (resp.) more than \( D \) after they were broadcast by their issuer, which contradicts the assumption of a bounded delivery delay, \( D \). (2) Suppose, by contradiction, that \( \text{age}_q(t') \neq \perp \). This implies that \( q \) received \( t' \) before \( t \), which corresponds to hypothesis (b) above, which is impossible under the bounded delivery delay assumption.

**Slow path: deterministic BBP commit.** We now focus on the slow path of NimbleChain. The slow path uses BBP as its back-end to agree on committing or discarding transactions. By taking advantage of the extensible design of BBP, we customize it with relatively simple extensions that enable NimbleChain to trigger deterministic BBP commit for specific transactions. These extensions affect the incoming transaction and chain validation routines\[^{[1]}\], which are external to BBP and, thus, can be modified without hurting the correctness of the underlying BBP. We provide details on our concrete extension of Ethereum in §6.1

Intuitively, the goal is to have any correct process \( p \) engage (through its local BBP node) in the deterministic BBP commit of some transaction \( t \) as soon as either: i) \( p \) has promised \( t \); or ii) \( p \) is aware that at least one other correct process may have already promised \( t \). NimbleChain implements the above goal by having each process \( p \) engage in the deterministic BBP commit of \( t \) as soon as \( \text{age}_p(t) \) reaches a value of \( AT - 2 \) (or higher).

To illustrate, let us consider the example depicted of Figure 3(top). In this example, at least one correct process \( p_A \) promises \( t \) (\( \bullet \) in Fig. 4) top), once \( \text{age}_{p_A}(t) = AT \). From Lemma 1 we know that any correct process \( p_B \) with a diverging view on \( t \)’s age will, in the worst case, have \( \text{age}_{p_B}(t) = AT - 2 = 2 (\bigcirc) \), with high probability. Therefore, every correct process (including \( p_A \) and \( p_B \)) will, with high probability, engage in the deterministic BBP commit of \( t \). This ensures that BBP’s slow path will eventually commit \( t \) (\( \bullet \)) with high probability. In fact, even if some correct processes do not promise \( t \) in their fast path – namely, if they receive a double-spend of \( t \) that prevents them from successfully ageing \( t \) (\( \bigcirc \)) – such processes will later promise-commit \( t \) once they learn about the slow path’s decision.

Figure 4 bottom illustrates another possible scenario where \( \text{age}_{p_1}(t) \) lies between \( 0 \) and \( 2 \) across different correct processes. In these scenarios, correct processes such as \( p_A \) reach a state with \( \text{age}_{p_1}(t) = 2 (\bigcirc) \) in Figure 4 bottom) and thus engage in the deterministic BBP commit of \( t \) and reject chains with any double-spending transaction \( t' \). In contrast, other correct processes such as \( p_B \) observe lower values of

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3. More precisely, inside the content validation predicate \( (V(\cdot)) \) and the environment (more precisely, where the input tapes of each process are determined) according to Garay et al.’s terminology \[^{[1]}\].
Fig. 4: Example of NimbleChain handling a transaction that is part of a double-spending attempt, with \( AT = 4 \). Top: transaction successfully ages (thus, is promised via fast path) in at least one correct process. Bottom: transaction does not successfully age in any correct process.

\( \text{age}_{pA}(t) \) and, thus, remain open to accept chains with either \( t \) or \( t' \) (5). This can be problematic if the Byzantine process that issued the double-spend further manages to extend the current main chain with a new block comprising \( t' \). In this situation, processes like \( p_A \) will reject such new chain, while processes like \( p_B \) will accept the new chain (by the longest chain rule of BBP).

We call this a fragmentation attack. It introduces an artificial fork that divides the mining power of correct processes across two fragments, denoted \( A \) and \( B \) in Figure 4. While the fragmentation persists, it may harm the robustness of BBP.

While the correct system is fragmented, the attacker’s mining power will be temporarily closer to the largest correct fragment’s mining power. In an extreme scenario, a resourceful attacker that manages to execute a successful fragmentation attack (or a series of fragmentation attacks) might benefit from temporary supremacy over the correct system. This would provide the attacker with an opportunity window to generate an alternative chain at faster than the system of correct processes. For instance, this faster generated chain could be used to commit a double-spending transaction \( t' \) that conflicts another transaction \( t \) that the correct system had previously promised or committed. Note that, to succeed, this attack requires that the temporary mining supremacy (as enabled by the fragmentation attack) last long enough for the attacker to generate \( C \) blocks.

Hence, NimbleChain needs to be able to self-heal upon any successful fragmentation attack. To explain how NimbleChain achieves that, Figure 4 bottom depicts the two possible scenarios that may occur upon a successful fragmentation attack. A first fragmentation scenario (6) is when the fragment of correct processes engaged in the deterministic BBP commit of \( t \) are able to grow their chain faster than the opposite fragment (holding a chain with \( t' \)), but not vice-versa. It is easy to show that this fragment will be naturally healed by BBP’s longest chain selection rule as soon as the main chain grows to be larger than the opposite fragment’s chain. This may require between 2 and \( C \) new blocks.

The second scenario (6), however, may take longer to heal. In the case where the fragment holding a chain with \( t' \) happens to have the majority of correct processes, then it is likely that this chain will tend to grow faster than the chain with \( t \). This implies that the chances of the above-mentioned merging with the \( t' \) chain will quickly drop to a negligible probability, which would tend to produce a permanent fragmentation.

NimbleChain prevents the possibility of a permanent fragmentation by employing a \( C \)-bounded deterministic BBP commit. Algorithm 2 presents this method, which we explain next.

The method is based on a notion that we call the required replacement suffix (RRS) for a transaction \( t \) on some process \( p \), or simply \( \text{RRS}_p(t) \). In its simplest formulation (ln. 3), \( \text{RRS}_p(t) \) is \( C \) for those transactions which \( p \) has aged to at least \( AT - 2 \) (i.e., the age that makes \( p \) engage in the deterministic BBP commit of a transaction); and 0 otherwise.

When a process \( p \) receives a new chain that contains some transaction \( t' \) that conflicts with a transaction \( t \) that \( p \) has seen before, the decision about whether to accept the conflicting chain is driven by the current value of \( \text{RRS}_p(t) \). More precisely, the conflicting chain is only accepted if the block containing \( t' \) is suffixed by at least \( \text{RRS}_p(t) \) blocks (ln. 5).

In practice, this condition has no effect when \( t \) has not yet aged up to \( AT - 2 \) (hence, \( \text{RRS}_p(t) = 0 \)). Otherwise, it means that \( p \) had already engaged in a deterministic BBP commit of \( t \) (thus, \( \text{RRS}_p(t) = C \)) and, as such, \( p \) will reject
any chain that contains any double-spend \( t' \) except if the block with \( t' \) is followed by at least \( C \) blocks in that chain – i.e., \( t' \) is committed. In this case, such process will accept the chain containing \( t' \) and, consequently, promise+commit \( t' \) and discard \( t \). Consequently, the C-bounded policy ensures that, in this worst-case scenario, the fragmentation is healed after \( C \) blocks are generated.

Finally, we remark that adopting a C-bound deterministic BBP commit approach (instead of an unbounded approach) still ensures that NimbleChain handles the first fragmentation scenario (5) robustly. Recall the assumption behind the persistence property of BBP: the probability that Byzantine processes are able to generate a fork of \( C \) blocks long (relatively to the main chain) faster than the correct processes is arbitrarily low. Further, consider the first fragmentation scenario where a correct process \( p_A \) promises \( t \) while correct process \( p_B \) with \( \text{age}_{p_B}(t) = 2 \) engaged in a C-bounded deterministic BBP commit of \( t \). Now, let us suppose, per impossible, that, before BBP commits \( t \), \( p_B \) accepts a chain where \( t' \) (a double-spend of \( t \)) is suffixed by \( C \) blocks – therefore not only \( p_B \) would commit \( t' \), but would also withdraw its contribution to the deterministic BBP commit of \( t \). However, for such a chain containing \( t' \) to exist, it must have been generated by Byzantine processes, which contradicts our initial assumption.

### 4.3 Trading fast path latency for robustness

The previous section showed that, with the minimal \( AT = 4 \) value, a single fragmentation attack may take up to \( C \) rounds to heal. In this section, we explain how NimbleChain can be configured to substantially mitigate the chances of success of the above attack. The key idea is that, by increasing \( AT \), NimbleChain can reduce the time it takes to heal fragmentation attacks from \( C \) to the time it takes for the fastest fragment’s chain to generate 2 blocks, with high probability. This improved robustness comes at the cost of a higher fast path latency.

Before describing how NimbleChain can reduce the above vulnerability window, let us recall the two fragmentation scenarios in Figure 4, which assume \( AT = 4 \). In both scenarios, every correct process has received transaction \( t \) and an attacker is mining an alternative chain that contains a double-spend transaction \( t' \). While some correct processes will accept the alternative chain as long as it meets the standard BBP requirements, others will be more reluctant and impose the additional constraint that, in the alternative chain, the block with \( t' \) must be followed by at least \( C \) blocks.

As shown in Figure 4 with \( AT = 4 \), \( RRSP_p(t) \) may differ between 0 and \( C \) for different correct processes. Intuitively, this upper bound on the divergence across \( RRSP_p(t) \) directly determines the time – in terms of block generation rounds – that a fragmentation attack may take to heal. Therefore, if we can lower this upper bound, ideally down to 1, we can minimize the healing time.

We achieve this by extending the algorithm described in the previous section with a progressive variant (in [11], Alg. 2) where each process gradually increments \( RRSP \) in \( 2D \) steps. More precisely, we define \( RRSP_p(t) = \lfloor \text{age}_{p}(t)/2 \rfloor \). To enable this progressive variant, while ensuring that \( p \) only promises transaction \( t \) once every correct process \( p_i \) is engaged in a C-bounded BBP commit of \( t \) (i.e., \( RRSP_{p_i}(t) = C \)), we need to redefine \( AT = 2(C + 1) \).

As an example, suppose that process \( p \) receives a transaction \( t \). Initially, \( RRSP_p(t) = 0 \). If \( p \) does not observe any double-spend of \( t \), \( RRSP_p(t) \) will grow to 1, 2, ..., every \( 2D \), until it reaches \( RRSP_p(t) = C \) once \( \text{age}_p(t) = C \times 2D \). Finally, \( 2D \) later, \( t \) successfully ages at \( p \) and, hence, \( p \) promises \( t \) at \( \text{age}_p(t) = 2(C + 1) \).

To understand the impact of this new configuration, Figure 5 revisits the fragmentation scenarios from Figure 4. As before, a successful fragmentation attack has split the set of correct processes into two divergent fragments: fragment \( A \), whose processes hold \( t \) in their local ledger and now have \( RRSP_{p_A}(t) = 1 \) (instead of \( RRSP_{p_A}(t) = C \) as per the original formulation); and fragment \( B \), whose processes have \( RRSP_{p_B}(t) = 0 \) and, consequently, have accepted a chain with transaction \( t' \), a double-spend of \( t \), which the attacker produced and disseminated. On the one hand, a process in fragment \( A \) does not accept the chain held by fragment \( B \), since it holds a block with a double-spend of \( t \) that is not suffixed by at least one block (due to \( RRSP_{p_B}(t) = 1 \)). On the other hand, a process in fragment \( B \) will not accept the chain of fragment \( A \) since it has a lower height than fragment \( B \)’s main chain (due to the longest-chain rule).

Let us first consider the scenario where fragment \( A \) is faster in extending its chain (5) than fragment \( B \). In this case, as soon as \( A \)’s chain grows 2 blocks, processes in \( B \) will start accepting that (according to the longest-chain rule). Let us, instead, analyse the reverse situation, where fragment \( B \)’s chain grows faster (6). The fragmentation may now heal as soon as fragment \( B \) appends a single new block to its chain. These represent substantial improvements in healing time relatively to the \( AT = 4 \) configuration, which could take up to \( C \) blocks to heal in worst-case scenarios.

We remark that the above upper bounds are also observed in concurrent scenarios, where more than one block is produced either at the same fragment or across different fragments. Furthermore, we highlight that the 1 or 2 blocks needed to heal a fragmentation can be produced by any process in either fragment, which means that the healing speed is determined by the aggregate resources of the correct nodes (i.e., not restricted to the largest correct fragment’s resources). For generality, it is easy to prove that these upper bounds on the healing time are also valid to scenarios where: i) the fragmentation attack occurs when \( t \) had a higher age; and, ii) the fragmentation attack simultaneously aims at multiple double-spending transactions. For space limitations, we omit the analysis of such scenarios in the paper.

Summing up, NimbleChain can be configured between two extremes and offer a trade-off between fast path latency and robustness against fragmentation attacks. Table 2 summarizes the trade-off between both extremes of \( AT \). For intermediate \( AT \) configurations, we can have \( RRSP \) grow in increments of \( k \) units such that \( 1 < k < C \).

### 4.4 Ensuring causal order

We now describe how NimbleChain handles causal dependencies consistently across the slow and fast paths. Dependencies are specified in an additional transaction field using...
some suitable causality tracking mechanism. Moreover, the mempool comprises two distinct queues: a ready queue, which contains the transactions that are ready to be included in the next block; and a pending queue, which contains transactions that, despite being valid, are still missing causal dependencies. More precisely, for any transaction \( t \) appended to the mempool’s ready queue, every transaction on which \( t \) causally depends on must already be promised in that process. Note that this condition implies that the transactions on which \( t \) causally depends will precede \( t \) in the local ledger’s order. Any valid transaction that does not (yet) satisfy the previous condition is temporarily enqueued in pending. Furthermore, whenever a process promises a new transaction, the dependencies in pending are re-evaluated and any transaction whose dependencies are satisfied is moved to the ready queue.

It is worth noting that the mempool of mainstream blockchain implementations already include both queues. For instance, in account-based blockchains (such as Ethereum), when a process receives a transaction with a sequence number that is not consecutive to the latest known transaction from the same account, it is placed in a pending queue until the gap in sequence numbers is filled. NimbleChain reuses such existing queue. Still, NimbleChain adds the additional condition that, besides sequence number dependencies, any explicit dependencies of the transaction must also be met before it is moved to the ready queue.

Further, NimbleChain ensures that any transaction in a block that a correct process tries to generate is preceded (in the corresponding chain order) by its causal dependencies. Moreover, causal dependencies are also enforced for transactions in chains received from processes – if the causal dependencies are not satisfied the chain is discarded.

Causal dependencies affect both paths of NimbleChain. Regarding the fast path’s ageing protocol, a transaction \( t \) that successfully ages will not be promised until all of its dependencies were promised. Concerning the slow path, the above-mentioned constraints ensure that the underlying BBP will only handle transactions whose causal dependencies are promised.

Finally, we remark that, while the algorithm described in the previous sections ensured that every transaction issued by a correct process would be promised via the fast path at every correct process, this no longer holds when transactions have causal dependencies. As an example, suppose that a correct process \( p \) has promised a transaction \( t_1 \) that was issued by a Byzantine process as part of a double-spend attempt; and, after observing \( t_1 \), \( p \) issues \( t_2 \), which causally depends on \( t_1 \). Recall that, since \( t_1 \) is part of a double-spending attempt, \( t_1 \) may not successfully age (i.e., be promised via fast-path) at some (or all) process. In that case, some (or all) processes will only promise \( t_1 \) via the slow path. Hence, even though \( t_2 \) was issued from a process that had promised \( t_1 \) via its fast path, the processes that had not done so will delay \( t_2 \)’s commit until the outcome of \( t_1 \) is determined by the slow path.

### 4.5 Correctness

We next prove that that NimbleChain, with high probability, satisfies the properties associated with the new promise event (as introduced in §3).

In the following, we assume that there is a negligible probability that an attacker, by spending a slice \( x \) of its mining power to perform a fragmentation attack (or a series of fragmentation attacks) for some period \( T \), manages to reduce the average mining power of the largest correct fragment by more than \( x \) during \( T \). In §5, we empirically support this assumption based on an experimental evaluation of NimbleChain when operating under fragmentation attacks.

**Theorem 1.** NimbleChain satisfies the eventually committed upon promised property with high probability; i.e., if a correct process promises a transaction \( t \) then all correct process eventually commit \( t \).

**Proof.** Assuming no causal dependencies. We start by considering the case where \( t \) has no causal dependencies. We distinguish two cases, depending on whether \( t \) is issued correctly or not.

**Case 1: \( t \) issued correctly.** In this case, the \( t \) will always successfully age at every correct process and, hence, every
process will promise \( t \). Furthermore, in this case, the slow-path commit of \( t \) simply follows BBP with no modifications. Therefore, since BBP guarantees the liveness property, every correct process (which inevitably promises \( t \)) will eventually commit \( t \).

**Case 2**: \( t \) issued by a Byzantine process as part of a double-spending attempt. Now, let us consider that \( t \) is issued by a Byzantine process that also issues at least one double-spending transaction \( t' \) with the same sequence number as \( t \). Consider \( T_0 \) as the time some correct process \( p \) promises \( t \). Therefore, at \( T_0 \), \( t \) has already aged at least \( AT \) at \( p \); consequently, by Lemma 1 at \( T_0 \), in every other correct process, \( t \) has aged for at least \( AT - 2 \). This implies that, at \( T_0 \), every correct process has engaged in a C-bound deterministic BBP commit. Hence, at \( T_0 \), every correct process will refuse to include \( t' \) in its mempool and will reject any chain containing \( t' \) unless \( t' \) is followed by \( C \) blocks in that chain. Let us assume, by contradiction, that, with non-negligible probability, at some later time, \( T_V \), process \( q \) is the first correct process that receives and accepts a chain with \( t' \) followed by \( C \) blocks, thereby committing \( t' \). From \( T_0 \) until \( T_V \), every correct process excludes \( t' \), while \( t \) is processed (as a valid transaction) by the correct system. Hence, during this period, the correct processes treat \( t \) in the same way as any transaction issued by a correct process (i.e., the processing of \( t \) is not affected by the fact that there is a conflicting transaction, \( t' \)).

By our initial assumption, with non-negligible probability, a correct process \( q \) commits \( t' \) at \( T_V \), upon receiving a chain that must have been produced by a Byzantine process (or system of processes). By BBP’s persistence property, this implies that no correct process had been able to commit \( t \) at \( T_V \). Therefore, our initial assumption allows a Byzantine process (or system of processes) to be able to generate, with a non-negligible probability, a \((C + 1)\)-long chain (the chain comprising a block with \( t' \) followed by \( C \) blocks) faster than the system of correct processes. This corresponds to Nakamoto’s formulation of a double-spending attack \([45]\), which constitutes a well-known violation of BBP’s persistence property. Therefore, the initial assumption must be false. Consequently, every correct process will eventually commit \( t \), which is the same transaction that \( p \) promised.

**Generalizing to causal dependencies.** We now generalize to transactions with non-empty causal dependency sets. This case can be proved by induction over the partial order defined by the causal dependency relation. Let us consider that transaction \( t \) depends on \( t_1, t_2, \ldots, t_n \) and a correct process \( p \) promises \( t \). The only difference in this case, when compared to cases 1 and 2 above, is that for a correct process \( q \) to commit \( t \), there is now an additional condition that must be met, i.e., that \( q \) has already committed \( t \)'s causal dependencies. Let us assume, by contradiction, that at least one causal dependency of \( t \), say \( t_i \), is never committed by \( q \), which consequently prevents \( t \) from ever committing at \( q \). By the causal order property, we know that, since \( p \) promised \( t \), then \( p \) must have already promised every causal dependency of \( t \), including \( t_i \). Therefore, the **eventually committed upon promised** property implies that \( t_i \) will eventually commit at every correct process, which contradicts the initial assumption.

**Theorem 2.** NimbleChain satisfies the causal order property with high probability; i.e., if a correct process promises (resp., commits) a transaction \( t \) then that process has already promised (resp., committed) every transaction on which \( t \) causally depends.

**Proof.** Suppose, by contradiction, that a correct process promises transaction \( t_2 \) before it has promised transaction \( t_1 \), where \( t_2 \) causally depends on \( t_1 \). This implies that \( t_2 \) had been added to \( p \)'s ready queue, which could only happen after \( p \) had promised \( t_1 \), which contradicts the initial hypothesis. The causal order regarding the commit event can also be proved by a similar contradiction argument. Assume, by contradiction, that correct process \( p \) commits \( t_2 \) before \( p \) has committed \( t_1 \), where \( t_2 \) causally depends on \( t_1 \). Hence, \( t_2 \) exists in a block in \( p \)'s local chain. This block has either been generated by \( p \) with transactions taken from \( p \)'s ready queue, or generated by another process and received by \( p \). In either way, since any transaction in a new block (generated or received by \( p \)) has its causal dependencies satisfied in the corresponding chain, then \( p \)'s chain also includes \( t_1 \) in a preceding position (in the same block as \( t_2 \) or in a preceding block). Consequently, if \( p \) committed \( t_2 \) since its block is suffixed by \( C \) blocks, then \( p \) must have committed \( t_1 \) before that instant. This contradicts the initial hypothesis.

Since NimbleChain’s slow-path consists of an instance of BBP customised with two extensions that do not modify the backbone protocol that is presented and analysed in \([12]\), the persistence and liveness properties of BBP are naturally satisfied by NimbleChain. Therefore, we skip the corresponding proofs.

### 5 Low-Latency Cryptocurrencies with NimbleChain

As discussed in \([24]\), a notable application that can benefit from the weaker guarantees of the promise event provided by NimbleChain is a cryptocurrency. We now detail how.

A cryptocurrency can be abstracted as as an instance of the asset-transfer object type defined by Guerraoui et al. \([21]\). An asset transfer object maintains a set of accounts, where each account is associated with an owner client that is the only one allowed to issue transfers withdrawing from this account. To do so, the owner client can invoke a **transfer**(a,b,x) to transfer x from account a to account b. There is a second operation, **read**(a), which every process can invoke to read the balance of account a.

Traditional permissionless blockchains, such as BBP, implement the asset-transfer object type by relying on the consensus-based commit event, as follows.

- **transfer**(a,b,x). When the process that owns account a wishes to execute **transfer**(a,b,x), it reads the current balance of a (see next) and, if the balance is sufficient, issues a new transaction whose payload transfers x from account a to account b.
- **read**(a). The **read**(a) operation is implemented by returning a’s balance from the state that results from the ordered execution of every committed transaction in the local chain.
Guerraoui et al. [21] prove that, in fact, the asset-transfer object type can be correctly implemented in a consensusless fashion. They also present (and prove correct) an actual consensusless implementation of the asset-transfer object type based on message passing. The algorithm they propose relies on a secure broadcast layer that exposes a broadcast and a deliver event (for messages), while offering uniform reliable delivery with source order guarantees despite Byzantine faults. The complete algorithm by Guerraoui et al. defines which state each process maintains in order to know, in an efficient way, which outgoing transactions have been issued by that process, as well as which incoming transactions have delivered and validated at that process. Further, it defines how, based on that state, the causal dependencies field of a newly-issued transaction can be efficiently encoded.

We can port their approach to NimbleChain by replacing the underlying secure broadcast layer with NimbleChain. Concretely, by simply replacing the broadcast and deliver events in Guerraoui et al.’s algorithm with the issue and promise events of NimbleChain’s interface. The key insight to this transformation is that the properties that Guerraoui et al. require from the secure broadcast layer (namely, integrity, agreement, validity and source order) are also satisfied by NimbleChain’s promises with high probability. We prove this later on this section.

Below, we present a high-level summary of the algorithm that results from porting Guerraoui et al.’s to rely on NimbleChain’s interface. For lower-level details, we refer the reader to [21].

- **transfer(a,b,x).** When a processes p that owns account a executes the transfer(a,b,x) operation, it confirms that account a has enough funds and, if so, issues a transaction t, whose payload describes the requested operation. Further, the causal dependencies field of the new transaction t is the set of transactions comprising: i) every previously issued outgoing transfer transaction (i.e., transferring funds from a); and ii) every incoming transaction (i.e., transferring funds to a) already promised by process p.

- **read(a).** The read(a) operation is implemented by returning a’s balance from the state that results from the ordered execution of every promised transaction in the local chain.

Recall that, for most transactions, NimbleChain’s fast-path ensures that most correct processes are able to promise such transactions much sooner than the time that BBP slow-path takes to commit them. Therefore, the above implementation of the asset-transfer object achieves important latency improvements.

The above promise-based implementation is correct according to the specification of the asset-transfer object type [21]. In other words, the above implementation correctly supports a cryptocurrency. The following lemma states this.

**Lemma 2.** The proposed promise-based implementation of transfer(a,b,x) and read(a) is a correct implementation of an asset-transfer object type [21].

**Proof.** To show that the above implementation is equivalent to Guerraoui et al.’s message passing asset-transfer object implementation, which was originally proposed and proved correct in [21], we prove that NimbleChain’s issue and promise events satisfy, with high probability, the properties of the secure broadcast layer underlying Guerraoui et al.’s implementation. We take the properties of the broadcast layer that underlies Guerraoui et al.’s algorithm (namely, integrity, agreement, validity and source order) and reformulate them by renaming the broadcast and deliver events by the issue and promise events (of our proposed blockchain model), respectively, the resulting properties are satisfied by NimbleChain with high probability.

**Integrity:** a correct process promises a transaction t from a process p at most once and, if p is correct, only if p previously issued t. This is ensured since transactions in BBP are digitally signed and carry a unique identifier.

**Agreement:** if processes p and q are correct and p promises t, then q promises t. Let us recall that, if a correct process p promises some transaction t, then p eventually commits t (by the eventually committed upon promised property). Hence, any other correct process q also eventually commits t (by BBP’s persistence property), thus, by definition of promise, q also promises t.

**Validity:** if a correct process p issues t, then p promises t. This is ensured since any transaction t issued by a correct process p is eventually committed by p (by BBP’s liveness property) therefore, by definition of promise, p also promises t.

**Source order:** if p and q are correct processes and both promise transactions t and t’, both issued by the same process r, then they do so in the same order. Let us first consider the case where t and t’ have the same sequence numbers. Therefore, the causal order property guarantees that both p and q will promise both transactions in order defined by their sequential numbers. Let us, instead, assume by contradiction that t and t’ have the same sequence number and are promised by p and q. Therefore, by the eventually committed upon promised property, p and q will eventually commit both transactions. Still, by definition, distinct transactions with the same sequential number are conflicting and, therefore, at most one of them can be committed. This contradicts the initial assumption.

We conclude with two final remarks. First, although Guerraoui et al.’s algorithm was originally proposed in the context of permissioned systems, adapting it to exploit NimbleChain’s primitives enables it the work in permissionless environments. Furthermore, while the original proposal supported a stand-alone cryptocurrency system, the above adaptation to NimbleChain integrates the low-latency cryptocurrency in a richer ecosystem where other applications with stronger consistency requirements may also co-exist. For instance, this hybrid consistency ecosystem enables processes to issue smart contract transactions (via the issue/commit interface), whose execution costs are charged from cryptocurrency accounts which may receive incoming transfers as defined above (via the issue/promise interface).

6 Evaluation

In this section, we evaluate NimbleChain with the goal of answering the following questions: i) what are the latency improvements that NimbleChain brings to applications with
different consistency needs, and ii) what is the impact of fragmentation attacks? Next, we detail the evaluation scenario, metrics and discuss our results.

6.1 Implementation, deployment and workload.

We implemented NimbleChain as an extension of Ethereum using the reference Geth 1.7 implementation [13]. The implementation required ≈ 3000 new lines of code to implement NimbleChain and changing ≈ 300 lines of code in Geth.

For experimental purposes, we also developed a custom client that, using the regular API, injects transactions in the system according to real transaction traces from Etherscan [15] (a sample of transactions from block 5306612 up to block 622336). The workload has no information about causality (aside from the implicit dependencies among transactions issued from the same account) and hence we set each transaction to depend on the most recently promised transaction – and, transitively, from the causal dependencies of that transaction. Note that this is a conservative choice, since it increases the probability that some NimbleChain processes will have to wait for causal dependencies.

To run experiments with a large number of processes we replaced the PoW component with a probabilistic mining selection process that follows a Poisson distribution and mimics the block production distribution.

To reflect the non-uniform mining power distribution of today’s mainstream permissionless blockchains, we allocated the estimated mining power of the top-13 most powerful mining pools of Ethereum to a subset of 13 processes (concretely, 24.0%, 21.3%, 13.2%, 12.1%, 5.7%, 1.9%, 1.8%, 1.5%, 1.4%, 1.3%, 1.1%, 1.0% and 1.0%, according to [15]). The remaining mining power was uniformly distributed across the remaining 487 processes.

We adjusted the block production probability to mimic Ethereum’s rate of 3 blocks per minute [15]. Moreover, we extended both NimbleChain and Ethereum implementations to log transaction events such as generation, reception, dissemination and state change and block events (such as insertion to the local chain and forks) to allow a posteriori offline processing for our evaluation. We use the same codebase, client and PoW component for the NimbleChain and Ethereum. Every correct process is parameterised with $C = 12$, the current standard commit threshold in Ethereum [61].

We ran each experiment for one hour with 500 processes for both NimbleChain and Ethereum, using 5 machines equipped with a mix of Intel(R) Xeon(R) CPUs. We empirically found this configuration of machines to be able to accommodate 500 processes without becoming overloaded and hence compromising the fidelity of the results. The processes run on an emulated network using Kollaps [20] with internet latencies to model the geo-distributed nature of permissionless blockchains. As suggested by previous measurement studies [18], [54], we used an average latency value of $120 ms$, and a conservative value for $D = 8 \times 120 ms = 960 ms$. Each node started with the same local chain, consisting of a single genesis block. We injected 8 transactions per second, as common in Ethereum [15]. All results are the average of 5 runs.

6.2 Promise and commit latencies

In this section, we study transaction latency as perceived from a process $p$, which we define as the time from the moment a given transaction $t$ is issued (at some process, not necessarily $p$) and the moment $p$ triggers the event that is required by the application semantics associated with $t$ (i.e., either promise or commit). We evaluate transaction latency for two transaction types, with distinct consistency needs: cryptocurrency transactions, which only require promises; and smart contract transactions, which need to be committed.

We consider 3 scenarios: i) 100% cryptocurrency transactions; ii) 100% smart contract transactions; iii) a mixed ratio of 44% cryptocurrency and 66% smart contract transactions as observed in Ethereum [54]. We evaluate these 3 scenarios considering no Byzantine behaviour. (We study Byzantine behaviour in the next section.)

We consider NimbleChain configured with $AT = 2(C + 1)$, the most robust configuration. Due to lack of space, we do not evaluate NimbleChain configured with $AT = 4$, which is a less robust configuration that would present even lower values for promise latency.

Figure 6 presents our results. As expected, the average transaction latency for cryptocurrency transactions is around one order of magnitude lower with NimbleChain (promise latency) than with Ethereum (commit latency), as shown in Figure 6 (top).
6.3 Fragmentation attacks

To perform a fragmentation attack (or a series of fragmentation attacks) for some period $T$, an attacker must allocate a portion $x$ of its mining power to that purpose during $T$. As a return from such investment, the attacker will reduce the average mining power of the largest correct fragment by $y$ during $T$. To be profitable to the attacker, $y$ must be higher than $x$. Otherwise, a rational attacker will not have any tangible benefit, and thus will not carry on the attack. The main goal of this section is to study the impact of fragmentation attacks, and consequently answer the above question.

Recall that a fragmentation attack involves broadcasting a transaction $t$ and immediately starting to produce a block with a double-spend $t'$. Later, the attacker broadcasts $t'$ in an attempt that different correct processes will receive it at different ages of $t$. This will result in some correct processes choosing $RRS_p(t) = a$ and others $RRS_q(t) = a+\delta$, where $a$ denotes the age that $t$ had when the former received $t'$ and $\delta$ depends on the $AT$ parameter (as discussed in §4.3).

We empirically found that the most advantageous case for the attacker was with $a=0$, i.e., some correct processes $p$ receive $t'$ when $age_p(t) = 0$, while other processes $q$ receive $t'$ when $age_q(t) > 0$ (i.e., either 1 or 2). Hence, in this analysis, we consider $a=0$.

As detailed in §4.3, the divergent fragments of correct processes eventually converge when at most 2 new blocks are generated from either fragment (and delivered), when $AT = 2(C+1)$. In contrast, when $AT = 4$, the divergent fragments of correct processes may require $C$ blocks to converge. In the meantime, the attacker may perform a burst of consecutive fragmentation attacks with the intention to keep the system fragmented for a longer period, by creating a new fragmentation before the current one is healed.

In these experiments, we assumed the attacker holds 24% of the resources, which corresponds to the largest mining pool in Ethereum [54]. The attacker continuously performs a fragmentation attack to weaken the aggregate resources owned by correct processes, by making them adhere to distinct fragments. The attacker uses its total mining power to perform the fragmentation attack series ($x = 24\%$). For space limitations, we omit scenarios where the attacker only spends a fraction of its total mining power ($x < 24\%$). Our analysis of lower values of $x$ yielded similar observations as the ones that we present next.

Further, we artificially instrumented the delivery protocol to ensure a fragmentation ratio that is favorable to the attacker: 80% of nodes randomly considered $RRS_p(t_1) = 0$ and could accept a malicious block immediately, while the remaining 20% considered $RRS_p(t_1) = 1$ for $AT = 2(C+1)$ or $RRS_p(t_1) = C$ for $AT = 4$. In a real scenario, it would be very unlikely for the attacker to be able to reach such precise fragmentation, since he does not control the network latency. We tested other values for the fragmentation ratio (e.g., 50%-50%, 70%-30% and 60%-40%), which yielded similar conclusions. Due to lack of space, we do not present them here.

Figure 7 shows the results as stacked histogram. The y-axis expresses the percentage of resources owned by each fragment and the x-axis represents time, in seconds. The

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Fig. 7: Fragment adoption during a fragmentation attack, comparing NimbleChain with $AT = 4$ (top) and $AT = 2(C+1)$ (middle) against the Ethereum baseline (bottom, no fragmentation attack) The y-axis expresses the percentage of resources owned by each fragment of correct processes, where 100% in the same colour (light grey) means that every correct process’ local chain is identical. The x-axis represents time, in seconds.

Fig. 8: Mining power utilization, average largest fragment CPU and fairness upon fragmentation attack.

Smart contract transaction commit times with Ethereum are very similar to NimbleChain’s, which suggests that the overhead of NimbleChain on the underlying protocol is negligible, as shown in Figure 3 (middle). NimbleChain seems to slightly outperform Ethereum at the head, due to slightly different transaction ordering criteria in the mempool. As an example, causal dependencies are ordered before a dependent transaction regardless of their price. Hence, such dependencies may reach the blockchain earlier in NimbleChain than in Ethereum.

Figure 3 (bottom) depicts the mixed scenario and shows an interesting trend. Cryptocurrency transactions continue to perform much faster in NimbleChain (promise latency) than in Ethereum (commit latency), while smart contracts commit at roughly the same pace with the results showing a clear inflection point between each transaction type.
light colored layer represents the percentage of resources owned by honest processes in the largest (i.e., with the highest mining power) fragment at a given moment. It is worth noting that, even in the baseline, the mere generation of a new block by a correct process (with or without a concurrent fork) causes short periods where the correct processes are not perfectly synchronized (i.e., in the same local chain state), which quickly end as the system synchronizes again. This is an intrinsic characteristic of BBP.

As expected, the results for $AT = 4$ (Figure 7 top) show a long-lasting fragmentation since processes require a long suffix of $C$ blocks before accepting a chain with $t_f'$. For $AT = 2(C + 1)$ (Figure 7 middle) we observe a much faster healing since processes require only 1 block before accepting a chain with $t_f'$. This confirms that $AT = 4$ trades a decreased latency in the fast path for less robustness against fragmentation attacks, while $AT = 2(C + 1)$ provides more robustness at the expense of a higher latency in the fast path.

To conclude our analysis of the fragmentation attack, we evaluate its impact on two metrics originally proposed by Eyal et al. [16]. The mining power utilization (MPU) is the ratio between the aggregate work of the main chain and all produced blocks. Fairness is the ratio between the number of blocks generated by the largest honest miner and all produced blocks. In a fair system, the fairness ratio should be identical to the mining power of the reference miner, which holds 21.3% mining power in this experiment (corresponding to the 2nd most resourceful miner). We also measure the average CPU power of the largest fragment.

The results are presented in Figure 8. As it is possible to observe, the MPU decreases from its baseline value when an attack is carried out. Further, MPU decreases as $AT$ decreases. The average CPU owned by the largest fragment during the attacks also decreases as $AT$ decreases. These are expected results, since the mining power is scattered among fragments.

Most importantly, the decrease in both metrics is considerably lower than the mining power the attacker invested to put the attack in practice. This is true even for the least robust variant of NimbleChain, $AT = 4$. This means that the attacker does not reach a break even point. Therefore, the analyzed attack is not profitable for a rational attacker. Instead of using his mining power to slow down the correct system’s ability to advance the main chain (through fragmentation), it would be more profitable for the attacker to employ the same mining power to accelerate the generation of his malicious chain (an attack vector that is possible in standard BBP). This observation empirically supports the assumption in [15] on the impact of fragmentation attacks.

Finally, and as expected, the fragmentation periods cause fairness deviations in NimbleChain. While vanilla Ethereum is the closest to the desired fairness target (ideally, 21.3%), the fairness of NimbleChain’s variants are still within a 10% distance from the ideal target.

7 Discussion

Assumptions on network propagation. The design of NimbleChain depends on the assumption of a well-known maximum delivery delay, $D$. Of course, NimbleChain may behave incorrectly if the $D$ assumption is not met by the underlying network. More precisely, a period of arbitrary propagation delays (beyond $D$) can violate our assumption that the age and $RSS$ that two correct processes assign to some transaction do not diverge by more than 2 and 1 (respectively). An arbitrary divergence across the ages each process sees may lead to pathological situations where two double-spending transactions are able to successfully age at distinct processes. Further, an arbitrary divergence in $RSS$ may compromise the ability of NimbleChain to heal upon a fragmentation attack.

We remark that a maximum network propagation time is a standard assumption in permissionless blockchains. For instance, every permissionless blockchain mentioned in §8 relies on this assumption. Further, different works have studied vulnerabilities that are possible if the $D$ assumption is violated. For instance, an unexpectedly high block propagation delay may slow down the time the system converges upon forks, which provides an advantage to a resourceful attacker to temporarily benefit from lower mining power utilization from the correct processes [17]. An eclipse attack [40] can isolate a subset of correct processes from the remaining correct system – which can be translated to arbitrarily increasing $D$ from the outside to the eclipsed partition –, allowing a resourceful attacker to control the evolution of the blockchain within the partition.

Still, we acknowledge that NimbleChain might be more sensitive than BBP to smaller sporadic violations of $D$, and/or smaller periods where $D$ is violated, during which NimbleChain’s properties are violated but BBP’s hold. This is a natural consequence of a protocol that reaches a decision over a shorter time window. This consequence is shared with every proposal in §8 that provides lower commit latencies than BBP.

Performance with higher delivery delays. In absolute terms, NimbleChain depends on $D$ being low enough to ensure a low fast path latency. Hence, one may rush to the conclusion that the speedup that NimbleChain introduces relatively to the baseline BBP-based permissionless blockchain depends on $D$. However, that is not correct. Let us suppose that NimbleChain was used in a low-quality network whose $D$ was much higher than the one that previous studies find in real permissionless blockchains [29], [30]. In that case, the PoW difficulty (and, hence, the block generation time, $B$) would need to be adjusted accordingly, in order to keep the $r = D/B$ rate low enough to ensure the (probabilistic) correctness of BBP. This readjustment of $D$ and $B$ would not only increase the fast path latency of NimbleChain, but also the commit latency of BBP. Therefore, the speedup of NimbleChain would remain the same. This conclusion is in line with Table 2 which shows that the speedup of NimbleChain depends on $f$ and $C$, not on $D$.

8 Related work

Improvements over longest chain rule. GHOST [58], partially implemented in Ethereum [61], improves Nakamoto’s original longest chain rule by allowing all blocks generated by honest participants to contribute to the commit of the main chain. This enables convergence even with higher block generation rates. A different approach, followed by inclusive blockchain protocols [53] and PHANTOM [57].
organizes blocks as directed-acyclic graphs (DAG) of blocks instead of a totally-ordered list in order to optimize performance. More recently, Conflux [35] combines the main principles behind GHOST and DAG-based solutions in an adaptive fashion to provide them with better liveness guarantees.

Despite the significant throughput gains (e.g., Conflux is able to improve GHOST’s throughput by 32x), these approaches still rely on consensus as the only path to commit. Consequently, they only bring modest commit latency savings (e.g., 25% latency gains in Conflux with respect to GHOST). NimbleChain can be plugged to any of these systems and enhance them with substantially lower commit latencies, while retaining their throughputs.

Hierarchical and Parallel Chains. Alternative blockchain organizations include hierarchical and parallel chains. In Bitcoin-NG [16], key blocks are generated at a similar rate as Bitcoin. Still, in-between two key blocks, the miner of the previous key block can generate many microblocks that contain transactions. FruitChain [48] adopts a similar hierarchical approach. OHIE uses parallel instances of BBP and then deterministically sorts blocks to reach a total order [62]. In all these proposals, the total order of the main chain is determined by only a fraction of blocks (key blocks). Hence, the remaining blocks (microblocks), which carry the actual transactions, can be safely generated at much higher rates than BBP allows, thus increasing throughput. Unlike NimbleChain, these proposals focus on improving throughput, not commit latency. For example, Bitcoin-NG does not improve commit latency [16] and OHIE’s average commit latency is around 10 minutes [62].

One notable exception is Prism [4], which supports low-latency and high-throughput honest transactions by resorting to parallel voting chains, which determine the total order of blocks in the main chain. Besides high throughput, Prism also improves commit latency. Still, their simulation-based evaluation results are around 2x higher than the causal commit latency of NimbleChain’s most robust configuration (40 to 58 sec with $\beta = 0.3$ [3]). Since all the above proposals are optimizations over BBP’s foundations, NimbleChain can supplement any of them with the low-latency of our consensusless fast path.

Blockchains based on Byzantine Fault Tolerance (BFT). A relevant body of proposals leverages BFT protocols, executed among small committees of processes, to improve the performance of permissionless blockchains. Proposals such as ByzCoin [31], Thunderella [49] and Solidia [11] combine BBP with BFT protocols. In contrast, proposals such as Algorand [19], HoneyBadger [44], and Stellar [57] are even more disruptive. These approaches can achieve comparable commit latencies as NimbleChain’s most robust configuration (40 to 58 sec with $\beta = 0.3$ [3]). Since all the above proposals are optimizations over BBP’s foundations, NimbleChain can supplement any of them with the low-latency of our consensusless fast path.

Sharding. Proposals such as Elastico [38], OmniLedger [32], Rapid-Chain [63], Monoxide [59] or Ethereum 2.0 [14] resort to multiple parallel blockchains cooperating via sharding, where a small committee maintains each shard. This approach achieves substantial throughput gains (up to thousands of transactions per second), however at the cost of security, since the smaller shards are vulnerable to powerful attackers. Since sharded proposals typically assume (multiple) BBP-based blockchain instances, NimbleChain can be generalized to supplement sharded proposals with a low-latency consensusless fast path. Some sharded proposals have also been shown to achieve comparable commit latency savings as NimbleChain (e.g., [52], [63]). Still, such results are possible in networks with much lower RTT than the one considered in our paper and only in specific best-case workloads.

Layer-2 proposals. Layer-2 proposals employ an additional protocol layer that handles (and commits) transactions and use the permissionless blockchain as a backend anchor to ensure consistency in the presence of malicious behaviour. In that sense, NimbleChain fits into this broad category. Among the most relevant proposals, so-called off-chain solutions such as the Lightning Network [52] and FastPay [25] rely on a separate network of payment channels and allow two or more parties to exchange currency without committing in the blockchain. However, these proposals have important shortcomings. They work at the expense of temporarily locking payment guarantees (often called collaterals) in the blockchain if a party misbehaves. While proposals based on payment networks are not tailored to unidirectional payment flows (as typical in retail payments from customers to merchants [41]), alternatives based on payment hubs [11], [24] either impose trusted entities or increased locked funds.

More recently, Snappy [41] proposes a novel on-chain smart-contract-based alternative that mitigates the above-mentioned shortcomings and achieves payment commit latency in the order of a few seconds. Still, Snappy has important scalability limitations in the number of payment recipient processes (up to 200 statekeeping merchants [41]). Further, since Snappy payments require smart contract invocations, they cost 8x more than simple transactions (in Snappy’s Ethereum-based implementation [41]). In contrast, NimbleChain neither requires collaterals, nor restricts scalability, nor increases transaction cost.

Proof-of-X alternatives. Another research avenue has proposed permissionless consensus algorithms that replace PoW with energy-efficient alternatives, such as Proof-of-Stake [28], [64], [19], [3], Proof-of-Space [12], [2] or Proof-of-Elapsed-Time [8]. Among such proposals, some are still based on a variant of BBP, despite replacing the PoW leader election component by a PoX alternative (e.g., [28], [64], [12], [2]). Therefore, NimbleChain’s consensusless fast path can be integrated onto such proposals.

Weakly-consistent blockchains. Like NimbleChain, some proposals attempt to obtain partial orders instead of total orders for cryptocurrency transactions. In the permissionless world, notable proposals include SPECTRE [56], TrustChain [46], ABC [53] and Avalanche [53]. In the context of permissioned blockchains, Astro [9] exploits Byzantine reliable broadcast [39] to build a payment system. All these proposals exploit the fact that cryptocurrency transfer transactions do not need to be totally-ordered, hence can be managed by weaker primitives than consensus. Like Nim-
bleChain’s consensusless fast path, the above proposals can serve the weak consistency needs of some applications such as cryptocurrencies. Still, these proposals cannot directly support general-purpose blockchains, whose application ecosystem comprises applications with weaker consistency demands (such as cryptocurrencies) and strong sequential consistency (such as most smart contracts). In contrast, NimbleChain’s hybrid consistency model is tailored to such mixed ecosystems.

Hybrid-consistency replication. The dichotomy between weak and strong consistency is well studied in the context of traditional geo-replicated systems [7]. It is well established that one needs to forfeit strong consistency to obtain the high availability, low latency, partition tolerance and high scalability that geo-replicated systems demand [7]. It is also known that many geo-distributed applications do not require strong consistency for every operation [35] and that many such applications are dominated by operations that are correct even if executed over a weakly-consistent view. This observation has motivated the advent of geo-replicated systems supporting hybrid (or mixed) consistency models [13], [42], [34]. To the best of our knowledge, NimbleChain is the first to introduce hybrid consistency models to permissionless environments.

9 Conclusions and future work
This paper proposes NimbleChain, which extends standard permissionless blockchains with a fast path that delivers consensusless promises of commitment. This fast path supports cryptocurrency transactions and only takes a small fraction of the original commit latency, while providing consistency guarantees that are strong enough to ensure correct cryptocurrencies. Since today’s general-purpose blockchains also support smart contract transactions, which typically have (strong) sequential consistency needs, NimbleChain implements a hybrid consistency model that also supports strongly-consistent applications. To the best of our knowledge, NimbleChain is the first system to bring together fast consensusless transactions with strongly-consistent consensus-based transactions in a permissionless setting.

Our evaluation conducted in a realistic geo-distributed environment with 500 processes shows that the average latency to promise a transaction is an order of magnitude faster than consensus-based commit. Overall, we believe that our approach of bringing fast transactions to permissionless blockchains as an extension to existing blockchains, rather than proposing a new system from scratch, is a step in the direction of bringing these results closer to adoption by de facto blockchain systems such as Ethereum or Bitcoin thus benefiting both the academic and industry communities.

Our work unveils new research avenues. Although this paper focuses on cryptocurrencies as the obvious application to benefit from the consensusless fast path of NimbleChain, our proposal can also provide important benefits to smart contracts which have (a subset of) transactions with weaker consistency needs. As an example, smart contracts that employ the ERC20 Token Standard [60] to transfer some asset may have weaker consistency needs. However, providing a hybrid consistency model to smart contract programs requires a careful integration of this model into smart contract execution runtimes, as well as providing programmers with the adequate abstractions to help them build smart contract methods that can safely run with weaker guarantees.

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