

Charlotte: Composable Authenticated Distributed Data Structures

Technical Report

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Abstract

We present *Charlotte*, a framework for composable, authenticated distributed data structures. Charlotte data is stored in *blocks* that reference each other by hash. Together, all Charlotte blocks form a directed acyclic graph, the *blockweb*; all observers and applications use subgraphs of the blockweb for their own data structures. Unlike prior systems, Charlotte data structures are composable: applications and data structures can operate fully independently when possible, and share blocks when desired. To support this composability, we define a language-independent format for Charlotte blocks and a network API for Charlotte servers.

An authenticated distributed data structure guarantees that data is immutable and self-authenticating: data referenced will be unchanged when it is retrieved. Charlotte extends these guarantees by allowing applications to plug in their own mechanisms for ensuring availability and integrity of data structures. Unlike most traditional distributed systems, including distributed databases, blockchains, and distributed hash tables, Charlotte supports heterogeneous trust: different observers may have their own beliefs about who might fail, and how. Despite heterogeneity of trust, Charlotte presents each observer with a consistent, available view of data.

We demonstrate the flexibility of Charlotte by implementing a variety of integrity mechanisms, including consensus and proof of work. We study the power of disentangling availability and integrity mechanisms by building a variety of applications. The results from these examples suggest that developers can use Charlotte to build flexible, fast, composable applications with strong guarantees.

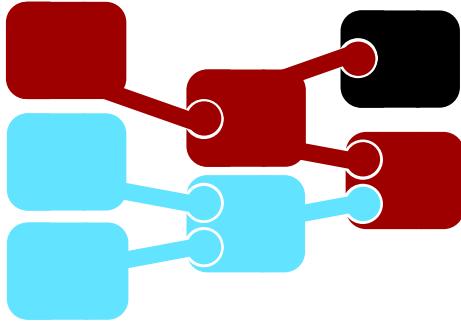


Figure 1: Blocks are represented as rectangles. References from one block to another are shown as circles. The pale blue blocks form a tree, whereas the darker red blocks form a chain. The rightmost red block references a blue block, so together the union of the red and blue blocks forms a larger tree. The black block also references a red block.

1 Introduction

A variety of distributed systems obtain data integrity assurance by building distributed data structures in which data blocks are referenced using collision-resistant hashes [54], allowing easy verification that the correct data has been retrieved via a reference. We call these *Authenticated Distributed Data Structures* (ADDSS). A particularly interesting example of an ADDS is a blockchain, but there are other examples, such as distributed hash tables as in CFS [14], distributed version control systems like Git [68], and file distribution systems like BitTorrent [12]. However, an ADDS does not automatically possess all properties needed by blockchains and other applications. An ADDS might fail to ensure availability, because a reference to data does not guarantee it can be retrieved. It might even fail to ensure integrity, because an ADDS might be extended in inconsistent, contradictory ways—for example, multiple new blocks could claim to be the 7th in some blockchain.

Therefore, an ADDS commonly incorporates additional mechanisms to ensure availability and integrity in the presence of malicious adversaries. Some systems rely on gossip and incentive schemes to ensure availability, and consensus or proof-of-work schemes to ensure integrity. Blockchains like Bitcoin [51] and Ethereum [19] lose integrity if the adversary controls a majority of the hash power, while Chord loses availability if an adversary controls enough consecutive nodes [67].

Importantly, all past ADDS systems lack *composability*: an application cannot use multiple ADDSs in a uniform way and obtain a composition of their guarantees. ADDSs from different systems cannot intersect (share blocks) or even reference each other. Lack of composability makes it difficult for applications to atomically commit information to multiple ADDSs. For instance, if blockchain ADDSs were composable, we could atomically commit a single block to two cryptocurrency blockchains, instead of requiring trusted clearinghouses.

A core reason for this lack of composability is that each system has its own set of failure assumptions. A user of Bitcoin or Ethereum, for example, must assume that at least half the hashpower is honest.¹ There is no mechanism for observers or applications to choose their own assumptions.

We address these limitations with *Charlotte*, a decentralized framework for composable ADDS with well-defined availability and integrity properties. Together, these ADDSs form the *blockweb*, an authenticated directed acyclic graph (DAG) [45] of all Charlotte data, which is divided into *blocks* that reference each other by hash. Charlotte

¹ There is some evidence that users need even stronger assumptions [18].

distills ADDSs down to their essentials, allowing it to serve as a common framework for building a wide variety of ADDSs in a composable manner, as illustrated by Figure 1.

Within the blockweb, different applications can construct any acyclic data structure from blocks, including chains, trees, polytrees, multitrees, and skiplists. Whereas blockchains enforce a total ordering on all data, the blockweb requires ordering only when one block references another. Unnecessary ordering is an enormous drain on performance; indeed, it arguably consumes almost all of traditional blockchains’ resources. Charlotte applications can create an ordering on blocks, but blocks are by default only partially ordered.

In Charlotte, each server stores whichever blocks it wishes. Most servers will want blocks relevant to applications they’re running, but some may provide storage or ordering as a service for sufficiently trusting clients.

Charlotte users can set their own (application-specific) failure assumptions. The failure assumptions of a user effectively filter the blockweb down to blocks forming an ADDS that remains available and consistent under all tolerable failures and adversarial attacks. An observer whose failure assumptions are correct can, given the assumptions of a different correct observer, calculate the subgraph of the blockweb they share.

A key novelty of Charlotte is its generality; it is not application-specific. Unlike other systems that build DAGs of blocks, Charlotte does not implement a cryptocurrency [53, 42, 57, 63, 64], require a universal “smart contract” language for all applications [27, 69, 34], have any distinguished “main chain” [52, 71], or try to enforce the same integrity requirements across all ADDSs in the system [37, 44, 72, 15, 7].

Instead, Charlotte distills ADDSs down their essentials, allowing it to serve as a more general *ADDS framework*, in which each application can construct an ADDS based on its own trust assumptions and guarantees, yet all of these heterogeneous ADDSs are part of the same blockweb. Indeed, existing block-DAG systems can be recreated within Charlotte, gaining a degree of composability. We have implemented example applications to demonstrate that Charlotte is flexible enough to simultaneously support a variety of applications, including Git-like distributed version control, timestamping, and blockchains based variously on agreement, consensus, and proof-of-work. The shared framework even supports adding shared blocks on multiple chains.

Contributions

- Our mathematical model for ADDSs (§3) gives a general way to characterize ADDSs with diverse properties in terms of observers, a novel characterization of different failure tolerances for different participants, and a general way to compose ADDSs and their properties.
- Charlotte provides an extensible type system for blocks, and a standard API for communicating them (§4).
- Example applications show the benefits of using the Charlotte model (§5).
- We generalize blockchains in the Charlotte model, including a technique for separating availability and integrity duties onto separate services and a general model of linearizable transactions on distributed objects (§6).

- We have implemented a prototype of Charlotte along with proof-of-concept implementations of various applications that demonstrate its expressiveness and ability to compose ADDSs (§7).
- Performance measurements show that Charlotte’s performance overheads are reasonable (§8).
- Analysis of real usage data shows that Charlotte’s added concurrency offers a large speed advantage over traditional blockchain techniques (§6.5).

2 Overview

2.1 Blocks

In Charlotte, blocks are the smallest unit of data, so clients don’t fetch “block headers,” or other partial blocks [19]. Therefore, Charlotte applications ideally use small blocks. For instance, to build something like Ethereum in Charlotte, it would be sensible to create the Merkle tree [48] structure found within each Ethereum block out of many small Charlotte blocks. This makes it easier to divide up storage duties and to fetch and reference specific data.

2.2 Attestations

Some blocks are *attestations*: they prove that an ADDS satisfies properties beyond those inherent to a DAG of immutable blocks. For instance, if a server signs an attestation stating that it will store and make available a specific block, it means the block will be available as long as that server functions correctly. Such an attestation functions as a kind of proof premised on the trustworthiness of the signing server. Attestations about the same blocks naturally compose: all properties of all attestations hold when all conditions are met.

All attestation types are *pluggable*: Charlotte servers can define their own subtypes, which prove nothing to observers who do not understand them. Charlotte is extremely flexible: application-defined attestation types can represent different consensus mechanisms (from Paxos to Nakamoto), different ADDS types, and different availability strategies. Although attestations can express a wide variety of properties about an ADDS, we divide them into two subtypes: *availability attestations* and *integrity attestations*.

2.3 Availability Attestations

Availability attestations prove that blocks will be available under certain conditions. One example of an availability attestation would be a signed statement from a server promising that a given block will be available as long as the signing server is functioning correctly. We call servers that issue availability attestations *Wilbur servers*.² Attestations may make more complex promises. For example, proofs of retrievability [6] might be used as availability attestations. Availability attestations are not limited to promises to store forever: they might specify any conditions, including time limits or

²after the *Charlotte’s Web* character whose objective is to stay alive.

other conditions under which the block is no longer needed. Availability attestations generalize features found in many existing distributed data systems:

- In BitTorrent, a seeder tells a tracker that it can provide certain files to leechers.
- Many databases inform clients that their transaction has been recorded by a specified set of replicas.
- In existing blockchains, clients wait for responses from many full nodes, to be sure their transaction is “available.”

2.4 Integrity Attestations

An ADDS often requires some kind of permission to add a block to its state. For example, a blockchain typically requires that some set of servers (“miners”) decide that a particular block uniquely occupies a given height in the chain. Integrity attestations determine which blocks belong in which ADDSs. For instance, servers maintaining a blockchain might issue an integrity attestation stating that a given block belongs on the chain at a specific height; the server promises not to issue any integrity attestation indicating that a different block belongs on the chain at that height. Timestamps are another integrity attestation type: they define an ADDS consisting of all blocks a specific server claims existed before a specific time. We call servers that issue integrity attestations *Fern servers*.³

Fern servers generalize ordering or consensus services. In blockchain terminology [51], they correspond to “miners,” which select the blocks belonging on the chain.

2.5 Life of a Block

Figure 2 illustrates one possible process for adding a new block to an ADDS. A client first mints a block, including data and references to other blocks. To ensure the block remains available, the client sends it to Wilbur servers, which store it and return availability attestations, demonstrating the availability of the block.

The client then submits a reference to the block to a collection of *Fern servers*, which maintain the integrity of the ADDS. Since Fern servers may not want to permanently add a block to their ADDS if that block is going to become unavailable, the client may also send availability attestations. Fern servers return *integrity attestations*, that, in effect, demonstrate the integrity of the statement “this block is in this ADDS.”

The client includes all of these attestations in references to the block, so that whenever an observer sees a reference to the block, they know how available it is, and what ADDSs it belongs to. Over time, more attestations may be issued, so a block can become more available or join more ADDSs, with greater integrity.

Charlotte is flexible: applications can optimize this process by co-locating services, forwarding attestations directly between servers, etc.

³after the *Charlotte’s Web* character who decides which piglets belong.

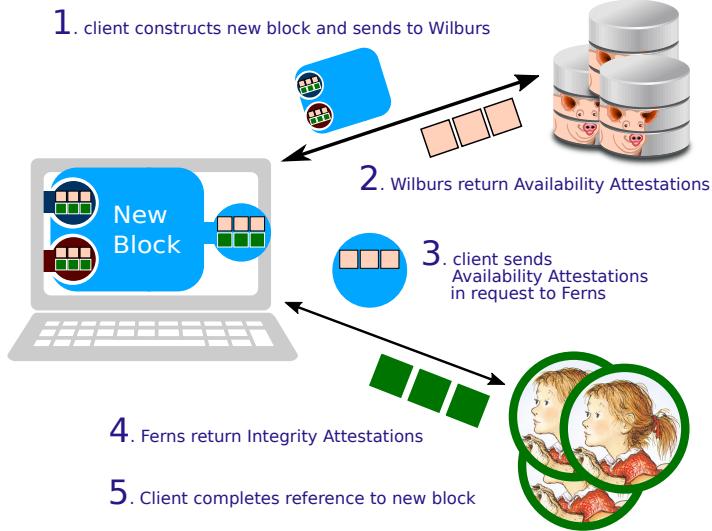


Figure 2: Life of a block. A client mints a new block, and wants to add it to an ADDS. The block, as drawn, includes two references to other blocks. The client acquires availability attestations from Wilbur servers, and integrity attestations from Fern servers. Then it can create a reference (drawn as a circle) to the block, so anyone observing the reference knows the block is in the ADDS.

2.6 Observers

We characterize an *observer* in a distributed system as an entity with a set of assumptions concerning the possible ways that the system can fail. Note that failure types include both Crash and Byzantine [41]. Given a set of assumptions about who can fail and how, and the desired integrity properties of each ADDS, each observer may choose to ignore any portions of the blockweb that lack adequate attestations. What remains is the observer’s *view* of the ADDS: the set of blocks it believes are available and part of the state of the ADDS.

Each observer’s view of an ADDS is guaranteed to remain available and to uphold any integrity properties the observer has chosen so long as the observer’s failure assumptions hold. Further, portions of the blockweb that feature attestations satisfying two observers are guaranteed to remain in both observers’ views, once both have observed all the relevant blocks. Of course, in practice, servers take time to download relevant blocks, and in an asynchronous system there is no bound on the time this may take.

2.7 Example Applications

Blockchains

Charlotte can easily represent blockchains—not only linear chains, but also more intricate sharded or DAG-based structures [45]. Existing blockchain systems already

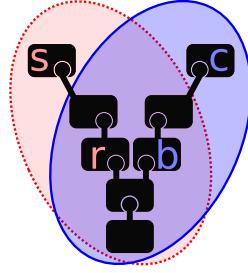


Figure 3: A blockchain ADDS with branches of length < 3 . All of the blocks are present in the blockweb. The red dotted oval and the blue solid oval represent two possible alternative states of the ADDS.

effectively provide integrity and availability attestations, phrased as proofs of work, proofs of stake, etc. Charlotte makes these proofs more explicit, without limiting the attestation types an application can use. As a result, multiple chains can share a block, if attestations required for each all refer to the same block. By providing a framework in which applications can interact, but without prescribing a rigid data structure, Charlotte allows far more concurrency than monolithic chains like Ethereum that totally order all blocks into a single chain [19]. This flexibility is a natural realization of the database community’s decades-old ideal of imposing a “least ordering” [5].

Distributed Version Control

Charlotte is also a natural framework for applications like Git [68]. Each Git *commit* is a block referencing zero or more parent commits. A commit with multiple parents is a *merge*, and a commit with no parents is a *root*. Each Git server stores and makes some commit blocks available, and can communicate this fact with availability attestations. A Git server can also maintain *branches*, which associate a branch name (a string) with a chain of commits. When a server announces that it is making a new commit the head of a branch, it issues an integrity attestation stating that the commit is part of the branch.

Public-Key Infrastructure

Public Key Infrastructure (PKI) systems are almost always ADDSs. Key endorsements are essentially integrity attestations, defining ADDSs such as the certificate trees used to secure HTTPS [31] and the web of trust used to secure PGP [9]. Keys and certificates can be retrieved by hash from dedicated storage servers such as PGP’s keyservers [28, 30, 60], corresponding to Wilbur servers. PKIs such as ClaimChain [38] already attest to and rely upon data structure properties, e.g., total ordering in chains.

3 Modeling ADDSs Formally

Different, possibly overlapping, portions of the blockweb represent ADDSs of interest to individual applications. We now explore Charlotte’s unique ability to allow different ADDSs to interoperate.

As a running example, consider a simple ADDS R representing a single, write-once slot managed by one server. It can either be empty, or occupied by one unchanging block.

3.1 States

A *state* is a set of blocks, and an *ADDS* is a set of possible states. For instance, the Bitcoin blockchain is an ADDS. Every block (other than the origin) in every state features a proof-of-work. A Bitcoin state can have an arbitrarily long main chain, and shorter branches. The Bitcoin ADDS consists of all such possible states.

In our single-slot example, each state of R is either empty, or features exactly two blocks: the block occupying the slot, along with an integrity attestation signed by the server, referencing that block. We call an integrity attestation in such a state i_x , where x is the other block in the state.

3.2 Observers and Adversaries

Observers represent principals who use the system. An observer receives blocks from servers and in so doing learns about the current and future states of ADDSs in the system. Observers may correspond (but are not limited) to servers, clients, or even people. Formally, an observer is an agent that *observes* an ordered sequence of blocks from the blockweb. On an asynchronous network, different observers may see different blocks in different orders.

Observers define their own failure assumptions, such as who they believe might crash or lie. These assumptions, combined with evidence, in the form of blocks they have observed so far, induce an observer’s *belief*: what they think is true about the blockweb now and what is (still) possible in the future.

The failure-tolerance properties of any distributed system are relative to assumptions about possible failures, including actions taken by adversaries. Charlotte makes these assumptions explicit for each observer. An observer who makes incorrect assumptions may not observe the properties they expect of some ADDSs. For instance, if more servers are Byzantine than the observer thought possible, data they believed would remain available might not. Alternatively, data structures might lose integrity, such as when two different blocks both appear to occupy the same height on a chain.

We characterize a belief α as a set of possible *universes*. This set bounds the believed powers of the adversary: the observer assumes this set includes all possible universes that might occur under the influence of the adversary. Figure 4 illustrates an observer holding a belief, and some of the universes in that belief.

Each observer has an *initial belief*: the belief it holds before it observes any blocks. For example, an observer who trusts one Fern server to maintain the single-slot ADDS R does not have any universes in its initial belief in which that server has issued two integrity attestations for different blocks. This belief encodes the observer’s assumption that the server’s failure isn’t tolerable. The observer in Figure 4 has such a belief: no universe features two integrity attestations for R (shown as green squares labeled i_x or i_y).

In a traditional failure-tolerant system, an observer usually assumes that no more than f participants will fail in some specific way (e.g., crash failures or Byzantine failures). We model such an observer’s initial belief as the set of all universes in which no more than f participants exhibit failure behaviors (in the form of blocks issued).

3.3 Formalizing Universes

We propose a general model for universes that places few limits on the details or assumptions universes can encode. Our model of a universe U has the following compo-

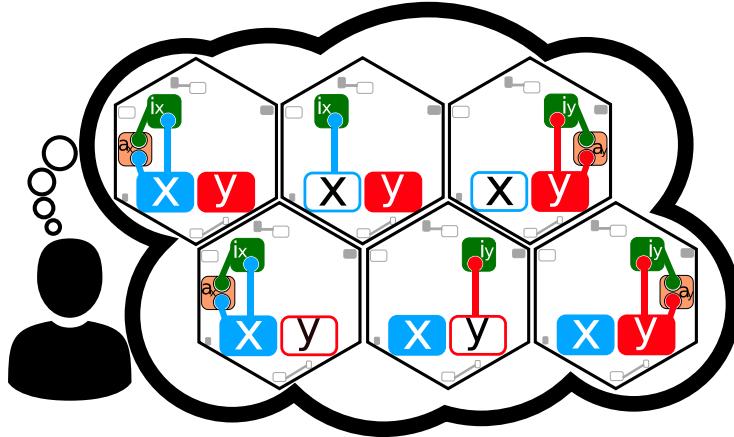


Figure 4: An *observer* holds a *belief*, which is a set of *universes*. Here we've drawn some universes as hexagons. Each universe U shown contains blocks in $\text{exist}(U)$, with blocks in $\text{avail}(U)$ filled in.

nents, which suffice for all examples in the paper.

1. A set of blocks that can *exist*, written $\text{exist}(U)$. These are the blocks that either have already been observed or ever *can* be observed by any observer.
2. A *strict partial order* \sqsubseteq on $\text{exist}(U)$. Every observer is assumed to observe blocks in an order consistent with the universal partial order \sqsubseteq .
3. The set of blocks that are *available*, written $\text{avail}(U)$. These are the blocks that can be retrieved from some server. Any available block must also exist: $\text{avail}(U) \subseteq \text{exist}(U)$.

The set $\text{exist}(U)$ constrains the blocks any observer will observe. It does not model time: an observer's initial belief contains universes representing all possible futures, with all blocks that are possible in each.

Since we are modeling asynchronous systems, the model does not explicitly include the time when blocks are observed, but the ordering \sqsubseteq constrains the times at which different observers can observe blocks, implicitly capturing a temporal ordering on blocks. This ordering is useful for blockchains like Bitcoin, where observers traditionally do not believe in any universe U unless there is a *main chain* in which each block b is ordered (by \sqsubseteq) before any equal-height block with which b does not share an ancestor fewer than security parameter k (usually 6) blocks away. Further, the *main chain* must forever outpace any other branch. In Figure 3, this belief (with $k = 3$) implies that if a Bitcoin observer believes in a universe U in which both blocks s and c exist, they must be ordered by \sqsubseteq . If Bitcoin's security assumptions are correct, any two observers must see s and c in the same order.

We make the simplifying assumption in each of our example applications that the only availability of interest is permanent: we want to characterize whether blocks will

forever be available. Hence, the set $avail(U)$ increases over time. We leave more nuanced availability policies to future work.

3.4 Updating Beliefs

As an observer observes blocks being created by Charlotte programs, it updates its beliefs by whittling down the set of universes it considers possible. For instance, if an observer with belief α observes a block b , clearly b *can exist*, so the observer refines its belief. It creates a new belief α' , filtering out universes in which b is impossible:

$$\alpha' = \{ U \mid b \in \text{exist}(U) \wedge U \in \alpha \}$$

If the observer in Figure 4 were to observe i_x , it would update its belief, retaining only universes U with $i_x \in U$. Of the universes shown, only the leftmost three would remain.

An observer also refines its belief by observation order: If an observer with belief α observes blocks B in total order $<_B$, then its new belief is:

$$\text{Possible}(\alpha, B, <_B) \triangleq \left\{ U \mid \begin{array}{l} \forall b' \sqsubseteq b. b' \in B \wedge b' <_B b \\ \wedge B \subseteq \text{exist}(U) \\ \wedge U \in \alpha \end{array} \right\}$$

An observer making no assumptions believes in all possible universes. It can only eliminate universes inconsistent with its observations: those in which blocks it has observed are impossible, or the order in which it has observed the blocks is impossible. However, most interesting observers have other assumptions. For example, the observer in Figure 4 trusts that only one integrity attestation for ADDS R will be issued, so if it observes i_x and removes all universes U without $i_x \in \text{exist}(U)$, then no universes with i_y will remain.

As another example, when a Git observer observes a valid integrity attestation for a block b , it can eliminate all universes with valid integrity attestations for blocks that are not descendants or ancestors of b .

3.5 Observer Calculations

An observer with belief α knows a set of blocks B are *available* if they're made available in all possible universes:

$$\forall U \in \alpha. B \subseteq \text{avail}(U)$$

For example, the observer in Figure 4 trusts availability attestations a_x and a_y (the orange squares): it does not believe in any universe where such attestations reference an unavailable block.

Likewise, an observer with belief α knows a state S of an ADDS D is *incontrovertible* if no *conflicting* state S' can exist in any possible universe. Two states conflict if they cannot be merged to form a valid state: observing one precludes ever observing the other:

$$\forall U \in \alpha, S' \in D. (S \cup S' \in D) \vee (S' \not\subseteq \text{exist}(U))$$

For example, the observer in Figure 4 trusts that only one integrity attestation for ADDS R will be issued. It does not believe in any universes with both i_x and i_y (shown as

green squares). Therefore, if it observes i_x , it knows the state $\{i_x, x\}$ is incontrovertible: no conflicting state (such as $\{i_y, y\}$) exists in any universe in its belief.

The state of ADDS D that an observer with belief α sees as available and incontrovertible is therefore:

$$\begin{aligned} \text{View}(\alpha, D) &\triangleq \\ &\bigcup \left\{ S \middle| \begin{array}{l} \forall U \in \alpha, S' \in D. (S' \subseteq S) \vee (S' \not\subseteq \text{exist}(U)) \\ \wedge \forall U \in \alpha. S \subseteq \text{avail}(U) \\ \wedge S \in D \end{array} \right\} \end{aligned}$$

We call this the observer's *view* of the ADDS: Charlotte's natural notion of the "current state." So long as an observer's assumptions are correct, new observations can only cause its view to grow. For example, if the observer in Figure 4 observes both a_x and i_x , then it believes the state $\{i_x, x\} \in R$ is available and incontrovertible. Its view of the single-slot ADDS R features x occupying the slot, and so long as its assumptions are correct, this will never change.

As another example, suppose a blockchain uses a simple agreement algorithm: a quorum of servers must attest to a block being at a specific height. States consist of a chain of blocks, each with integrity attestations from a quorum. An observer's view will not include any blocks lacking sufficient attestations. The observer assumes that no two blocks with the same height both get a quorum of attestations, so the chain it has viewed must be a prefix of the chain in any future view.

One observer can calculate what another observer's view of an ADDS would be, if they see the same observations. When two observers communicate, they can share blocks they've observed. Because new observations can only cause a view to grow, this allows one observer to know (at least part of) another observer's view when they communicate. This is what we mean when we say views in Charlotte are *consistent*: two observers can know what the other views in the same data structure, and so the state of a data structure can be, in a sense, global.

3.6 Composability

Recall that a *state* is a set of blocks, and an ADDS is a set of states (§3.1). ADDSs in Charlotte have two natural notions of composition: *union* (\uplus) and *intersection* (\sqcap).

3.6.1 Union

Intuitively, the union of two ADDSs D and D' is all the data in either ADDS. As states are sets of blocks (§3.1), their union is simply the traditional union of sets. Thus, the union ADDS is composed of unions of states:

$$D \uplus D' \triangleq \{ S \cup S' \mid S \in D \wedge S' \in D' \}$$

As a result, given an observer's failure assumptions, its view of the union of two ADDS is simply the union of its views of the ADDSs:

Theorem 1.

$$\forall \alpha, D. \text{View}(\alpha, D \uplus D') = \text{View}(\alpha, D) \cup \text{View}(\alpha, D')$$

Proof. Follows from the definitions of *View* and \uplus . \square

For example, a Git branch (§2.7) is a ADDS maintained by one server. A Git repository is the *union* of many branches with the same root, on the same server. Each branch ADDS has properties, such as linearity, not necessarily shared by the repository as a whole. However, the properties of all the ADDSs in a *union* can be combined to create properties that hold of the whole. For example, one server makes available all the blocks in all the branches of a repository. That means that the repository remains available so long as the server is correct. See §3.5 for more details.

3.6.2 Intersection

Intuitively, the intersection of two ADDSs D and D' is all the data that is in both D and D' . As states are sets of blocks (§3.1), their intersection is simply the traditional intersection of states. Thus, the intersection of ADDSs is composed of the intersections of states:

$$D \pitchfork D' \triangleq \{ S \cap S' \mid S \in D \wedge S' \in D' \}$$

As a result, given an observer's failure assumptions, its view of the intersection of two ADDS is simply the intersection of its views of the ADDSs:

Theorem 2.

$$\forall \alpha, D. \text{View}(\alpha, D \pitchfork D') = \text{View}(\alpha, D) \cap \text{View}(\alpha, D')$$

Proof. Follows from the definitions of *View* and \pitchfork . \square

For example, consider two blockchains, each serving as a ledger for a different crypto-currency. The blocks that are part of both chains represent transactions atomically committed to both ledgers. These are the natural place to put *cross-chain transactions*: trades involving both crypto-currencies. Thus, the intersection of the two blockchains is the sequence of cross-chain transactions.

The intersection ADDS shares the properties of all intersected ADDSs. In our blockchain example, the cross-chain blocks remain totally ordered by the blockweb so long as either component blockchain remains totally ordered by the blockweb (a traditional integrity property of blockchains). Furthermore, cross-chain blocks remain available so long as the blocks of either component blockchain remain available. See §3.5 for more details.

3.7 Availability Attestation Semantics

Observers use availability attestations to determine which blocks they consider sufficiently available to be in ADDSs they care about (§2.3). Formally, subtypes τ of availability attestation (which is in turn a subtype of blocks) have values that guarantee some blocks are available in some universes. To describe the guarantees offered by an availability attestation, we give a type τ an interpretation $\llbracket \tau \rrbracket$ that is a *belief*: that is, a set of universes in which availability attestations of that type are inviolate (§3.2).

For instance, consider the availability attestation subtype $\tau_{AliceProvides}$. Values of this type are blocks of the form $aliceProvides(b)$ (where b is another block). Intuitively, each value states that Alice (a Wilbur server) promises to make the specified block b available forever. Thus, all universes U in $\tau_{AliceProvides}$ in which $aliceProvides(b)$ exists also have b available:

$$\begin{aligned} \llbracket \tau_{AliceProvides} \rrbracket &\triangleq \\ \{U \mid \forall b. \text{aliceProvides}(b) \in \text{exist}(U) \Rightarrow b \in \text{avail}(U)\} \end{aligned}$$

Defining attestations this way makes it easy to define observers' beliefs based on *whom* they trust. For instance, if an observer believes a block will be available only if it has observed appropriate attestations of both type τ *and* type σ , we define that belief α as $\alpha = \llbracket \tau \rrbracket \cap \llbracket \sigma \rrbracket$.

Likewise, a more trusting observer who believes a block is available if it has observed appropriate attestations of type τ *or* type σ would believe $\alpha = \llbracket \tau \rrbracket \cup \llbracket \sigma \rrbracket$. In this way, we can even build up quorums of attestation types (e.g., $(\llbracket \tau_1 \rrbracket \cap \llbracket \tau_2 \rrbracket) \cup (\llbracket \tau_2 \rrbracket \cap \llbracket \tau_3 \rrbracket) \cup (\llbracket \tau_1 \rrbracket \cap \llbracket \tau_3 \rrbracket)$).

There are some restrictions on the semantics of an availability attestation type. Attestations must be *monotonic*: adding more attestations never proves weaker statements:

$$\forall U, V, W \in \llbracket \tau \rrbracket. \ exist(U) \cup exist(V) \subseteq exist(W) \Rightarrow \\ avail(U) \cup avail(V) \subseteq avail(W)$$

3.8 Integrity Attestation Semantics

Integrity attestations (§2.4) are issued by Fern servers (§4.2), and represent proofs guaranteeing the *non-existence* of other integrity attestations, under certain circumstances. While this definition may seem counter-intuitive, it generalizes the notion of *conflict* or *exclusivity* in ADDSs. For example, in our single-slot ADDS R , all the integrity attestations found in any state of R are mutually exclusive. Since each (non-empty) state of R contains an integrity attestation, the existence of one attestation disproves all conflicting states, which puts the attestation, and the block it references, in the view of any observer with an appropriate belief.

Formally, a subtype τ of integrity attestation has values that guarantee some other blocks *will not exist* in some universes.

Thus, we represent every attestation type τ as a set of universes, essentially a *belief* (§3.2) in that type. To describe integrity attestations' guarantees, we have a static semantics where types are identified with *beliefs*, sets of universes in which integrity attestations of that type are inviolate (§3.2).

For example, consider $\tau_{BobCommits}$, a subtype of integrity attestation with values that are blocks of the form $bobCommits(b)$, which intuitively indicates that Bob (a Fern server) promises never to commit to any block other than b . These integrity attestations are much like the ones used in our single-slot ADDS R .

Thus, all universes U in which $bobCommits(b) \in \exists U$ don't feature $bobCommits(c)$ for any $c \neq b$:

$$\llbracket \tau_{BobCommits} \rrbracket \triangleq \\ \left\{ U \middle| \forall b, c. b \neq c \Rightarrow \left\{ bobCommits(b), \right\} \not\subseteq exist(U) \right\}$$

integrity attestation types with these semantics make it easy to define observers' beliefs based on *who* they trust. For instance, an observer who believes b is committed only after receiving an attestation of type τ and an attestation of type σ would believe $\alpha = \llbracket \tau \rrbracket \cup \llbracket \sigma \rrbracket$. Likewise, a more trusting observer who believes b is committed after receiving an attestation of either type τ or σ would believe $\alpha = \llbracket \tau \rrbracket \cap \llbracket \sigma \rrbracket$.

It is also possible to combine integrity and availability attestation types to define a belief. An observer who trusts attestations of type τ to commit blocks, and attestations of type ρ to ensure their availability would believe: $\gamma = \llbracket \tau \rrbracket \cap \llbracket \rho \rrbracket$. In this way, we can even define quorums of trusted types.

```

1 message AnyWithReference {
2   google.protobuf.Any any;
3   Reference typeBlock;
4 }
5 message Hash {
6   oneof hashalgorithm_oneof
7   { AnyWithReference any;
8     bytes sha3; } } //technically unnecessary
9 message Reference {
10  Hash hash;
11  repeated Hash availabilityAttestations;
12  repeated Reference integrityAttestations;}
13 message Block {
14   oneof blocktype_oneof
15   { AnyWithReference any;
     string protobuf; } }
```

Figure 5: Core Types of Charlotte: this (slightly simplified) proto3 code describes how blocks, references to blocks, and generic data are safely marshaled and unmarshaled in Charlotte.

The definition of $Possible([\tau], B, <_B)$ (from §3.2) guarantees integrity attestations are *monotonic*: adding more attestations never proves weaker statements:

$$C \subseteq B \Rightarrow Possible(\tau, B, <_B) \subseteq Possible(\tau, C, <_B)$$

3.9 Implementation Limitations of Attestations

Since programmers can define their own subtypes of integrity or availability attestations, nothing prevents them from encoding availability guarantees in an integrity attestation, or violating the availability attestation monotonicity requirement (§3.7). Programmers who violate the system assumptions naturally lose guarantees.

In our implementation, the only operational distinction between an availability attestation and an integrity attestation is in the Reference object. When one block references another, it can also reference relevant integrity and availability attestations. However, whereas an included reference to an integrity attestation is itself a Reference object, an included reference to an availability attestation carries only a Hash. This is because an integrity attestation might need an availability attestations to describe where to obtain the integrity attestation. However, the same is not true of an availability attestation: it is pointless to send availability attestation b just to describe where to fetch availability attestation a , since it is just as easy to send availability attestation a in the first place.

4 Charlotte API

Charlotte is a set of protocols by which clients, Fern servers, and Wilbur servers interact. Different servers can run different implementations of these protocols. Our implementation of Charlotte (§7) uses gRPC [25], a popular language-independent network service specification language, based on Protocol Buffers [55]. Hence, we use Protocol Buffer (protobuf) syntax to describe the Charlotte protocols.

```

1 message SendBlocksResponse {
2   string errorMessage;
3   service CharlotteNode {
4     rpc SendBlocks(stream Block)
5       returns (stream SendBlocksResponse) {}

```

Figure 6: All Charlotte servers implement the CharlotteNode service.

Figure 5 presents the core types used by Charlotte protocols, using Protocol Buffer syntax.⁴ Charlotte is built around these core types:

- **Block**: can contain any protobuf [55] data type, or the block itself can be a protobuf type definition. Attestation is a subtype of Block. It can contain any protobuf [55] data type, and the block itself can be a protobuf type definition.
- **Hash**: represents the hash of a block.
- **Reference**: is used by one block to reference another; it contains the Hash of the referenced block, along with zero or more references to attestations (§2.2).
- **AnyWithReference**: Anyone can add their own subtypes of Block, Hash, or Attestation, which any server can safely marshal and unmarshal. It contains a reference to the block where the type description can be found (as proto3 [55] source code), and marshaled data.⁵

In practice, we provide some useful example subtypes of Hash (e.g., sha3) and Block (e.g., Attestation).

In our API, all Charlotte servers must implement the SendBlocks RPC (Figure 6), which takes in a stream of blocks and can return a stream of responses that may contain error messages. We define subtypes of attestation for *Availability* and *Integrity*, and show how to construct and observe from quorums of types they trust (§3.7 and §3.8).

4.1 Wilbur

Wilbur servers host blocks, providing *availability*.

In blockchain terminology [51], Wilbur servers correspond to “full nodes,” which store blocks on the chain. In more traditional data store terminology, Wilbur servers are key-value stores for immutable data. The Charlotte framework is intended to be used for building both kinds of systems.

In our API, Wilbur servers are Charlotte servers that include the RequestAvailabilityAttestation RPC (Figure 7), which accepts a description of the desired attestation, and returns either an error message, or a reference to a relevant availability attestation.

4.2 Fern

Fern servers issue *integrity attestations*, which define the set of blocks in a given ADDS. Among other things, integrity attestations can be proofs-of-work, or records

⁴ For simplicity, our specifications omit the indices of the various fields. The actual source code is also slightly more complicated for extensibility [2].

⁵ The proto3 Any type itself features a URL string meant to reference the type definition, but Charlotte uses a block reference because it is self-verifying.

```

1 message AvailabilityPolicy {
2     oneof availabilitypolicytype_oneof {
3         AnyWithReference any; }
4     }
5     message RequestAttestationResponse {
6         string errorMessage;
7         Reference reference;
8     }
9     service Wilbur {
10        rpc RequestAvailabilityAttestation(
11            AvailabilityPolicy)
12        returns (RequestAttestationResponse){}
13    }

```

Figure 7: Wilbur Service Specification.

```

1 message IntegrityPolicy {
2     oneof integritypolicytype_oneof
3     { AnyWithReference any; }
4     }
5     service Fern {
6         rpc RequestIntegrityAttestation(
7             IntegrityPolicy)
8         returns (RequestAttestationResponse){}
9     }

```

Figure 8: Fern Service Specification.

demonstrating some kind of consensus has been reached. One simple type of integrity attestation, found in our prototype, is a signed pledge not to attest to any other block as belonging in a specific slot in an ADDS. Fern servers generalize ordering or consensus services. In blockchain terminology [51], Fern servers correspond to “miners,” which select the blocks belonging on the chain.

In our API, Fern servers are Charlotte servers that include the RequestIntegrityAttestation RPC (Figure 8), which accepts a description of the desired attestation, and returns either an error message or a reference to a relevant integrity attestation.

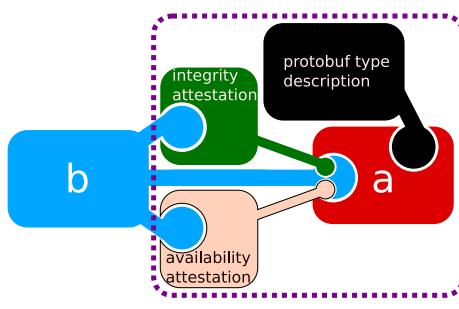


Figure 9: Block a references block b , and that reference carries attestations. Block a also references a type description block, for unmarshaling data in a . In general, when sending block a to a server or client, the sender should be sure the recipient has received *all* the blocks in the dashed purple rectangle, so the recipient can fully understand block a and the properties of its references.

4.3 Practices for Additional Properties

In order to understand a reference object within a block (how available the referenced block is, and data structures it's in), an observer reads attestations referenced within the reference object.⁶ For example, without the content of the availability attestations, it's not clear where to look to retrieve the referenced block. As a rule of thumb, before one server sends a block to another, it should ensure the recipient has any attestations or type blocks referenced within that block. This ensures the recipient can, in a sense, fully understand the blocks they receive. In Figure 9, for instance, when sending block a , the sender should be sure the recipient has received everything in the dashed rectangle. Our example applications follow this practice. It is possible, however, that for some applications, servers may be certain the recipient doesn't care about some attestations or type blocks, and therefore might leave those out.

When servers follow this practice, it's useful for availability attestations to attest to groups of blocks likely to be requested together. In Figure 9, for instance, an availability attestation that attests to everything in the dashed rectangle would be more useful than just attesting to block a . Our example applications' availability attestations are generally designed this way.

Availability failures can cause available states of ADDSs to become disconnected subgraphs (if the blocks that connect them are forgotten). To build an ADDS that will always remain connected, availability attestations that attest to a block should also attest to the availability attestations referenced within that block. Furthermore, whenever a block x references a block y , and block y references block z , if y isn't at least as available as z , then x should reference z as well. (Here, "isn't at least as available" means that the availability attestations in references to z guarantee z will be available in some universe where the availability attestations in references to y do not guarantee y will be available.)

⁶ We considered making references contain full copies of attestations, but this made blocks large, and since many blocks may reference the same block (and attestations), blocks were full of redundant information.

```

1 message WilburQueryInput {
2   oneof wilburquery_oneof {
3     Reference reference = 1;
4     Block fillInTheBlank = 2; }}
5 message WilburQueryResponse {
6   string errorMessage = 1;
7   repeated Block block = 2; }
8
9 service WilburQuery {
10   rpc WilburQuery(WilburQueryInput)
11     returns (WilburQueryResponse) {}}

```

Figure 10: WilburQuery Specification.

5 Use Cases

In addition to the examples mentioned earlier (§2.7), Charlotte is well-suited to a wide variety of applications.

5.1 Verifiable Storage

Our Wilbur specification provides a common framework for verifiable storage. Because ADDS references include hashes, it is always possible to check that data retrieved was the data referenced. Furthermore, availability attestations (§3.7) are a natural framework for proofs of retrievability [6].

5.1.1 Queries

In addition to `SendBlocks` and `RequestAvailabilityAttestation`, Wilbur servers may offer other interfaces. Application designers may wish to implement query systems for retrieving relevant blocks. We created one such example interface, the `WilburQuery` RPC (Figure 10). Given a Hash as input, `WilburQuery` returns the block with that hash. If the server does not know of such a block, our example implementation waits until one arrives.

`WilburQuery` also provides a kind of fill-in-the-blank match: If sent a block with some fields missing, `WilburQuery` returns the all stored blocks that match the input block in the provided fields. For example, we might query for all blocks with a field marking them as a member of a certain ADDS.

5.2 Timestamping

Timestamps are a subtype of integrity attestation. We implemented a Signed Timestamp type, wherein the signer promises that they have seen specific hashes before a specific time. Our timestamping Fern servers can use *batching*: they wait for a specific (configurable) number of new requests to arrive before issuing a Timestamp block referencing all of them. In fact, since hash-based references represent a *happens-before* relationship [39], timestamps are transitive: if timestamp *a* references timestamp *b*, and *b* references *c*, then *a* effectively timestamps *c* as well.

We recommend that batch Timestamp blocks themselves should be submitted to other Timestamping Fern servers. This allows the tangled web of Timestamp blocks to very quickly stamp any block with exponentially many timestamps, making them very high-integrity.

5.3 Conflict-Free Replicated Data Types

Charlotte, and ADDSs in general, work well with CRDTs, especially Operation-Based Commutative Replicated Data Types (CmRDTs) [59]. CmRDTs are replicated objects maintained by a group of servers. Whenever a new operation originates at any server, all known operations on that object on that server are said to *happen before* it. Then the operation asynchronously propagates to all other servers. Thus, the set of operations known to any particular server are only partially ordered. The *state* of a CmRDT object is a deterministic function of a set of known operations (and their partial order). For example, a CmRDT implementation of an insert-only Set might feature the `insert` operation, and its state would be the set of all arguments to known `insert` operations.

In Charlotte, CmRDT operations can naturally be expressed as blocks, with *happens-before* relationships expressed as references. Since references are by hash, it is impossible for an adversary to insert a cycle into the graph of operations. The states of a CmRDT can be formally expressed as all possible sets of operations with all possible partial orderings.

Aside from whatever credentials one needs to authorize an operation, CmRDTs do not need integrity attestations. Observers need only consider the graph of known, valid operation blocks with known ancestry. They may, of course, choose to filter out blocks they consider insufficiently available. Availability attestations are still useful.

The blockweb as a whole is a CmRDT: Its state is the DAG of all blocks, and every block is an operation adding itself to the state. Other than the blockweb itself, however, we have not implemented any interesting CRDTs yet.

5.4 Composition

Charlotte ADDSs are easy to compose (§3.6). At the most basic level, blocks in one ADDS can reference blocks in another. For instance, a Timestamp server might maintain a chain of timestamp blocks, which reference any other blocks people want timestamped (Git commits, payments, documents, etc.). A Git-style repository might reference earlier commits in another repository (either because one is a fork of the other, or one has merged in code from another) without having to copy all of the data onto both servers. This would resemble Git’s *submodule* system [11]. A blockchain could reference a Git commit as a smart contract, instead of hosting a separate copy of the code [19]. A single block of data, stored on some highly available servers, could be referenced from a variety of torrent-style filesharing applications, git-style repositories, and blockchains, without unnecessary duplication.

At a high level, composability allows us to build high-integrity ADDSs out of low-integrity ones (§3.6). For instance, the blocks that appear in the intersection of two chains form a chain that can only fork if *both* component chains fork. Users may want to put especially important blocks on many different chains, the way they want many different witnesses for important legal transactions.

Likewise, we can build low-integrity ADDSs out of higher integrity ones (§3.6). If a set of blockchains each manage independent tokens, and sometimes share blocks (for

atomic trades of tokens), then together all the chains form a DAG. If *any* chain in the DAG is corrupted, then the supply of that token may not be conserved: the DAG as a whole is lower integrity than any one chain. This makes it possible to talk about the “integrity of the marketplace” as distinct from the integrity of any one token.

5.5 Entanglement

Some attestations, such as timestamps §5.2, and proofs of work §6.2.1, implicitly lend integrity to everything in a block’s ancestry. When many ADDSs reference each other’s blocks, these recursive attestations can make some forms of fraud very difficult. For example, if many applications regularly reference past timestamps, and many applications request timestamps from a variety of servers, it quickly becomes difficult to falsely claim a block *did not* happen before a given time, when doing so would involve hiding evidence embedded in many different applications.

6 Blockchains as ADDSs

Charlotte is an ideal framework for building new blockchains and related applications (§2.7). In the simplest sense, a blockchain is any path through the blockweb. However, most existing blockchain applications are considerably more complicated.

Like all ADDSs, a blockchain needs *integrity* and *availability*. Here, integrity means that an observer’s view (§3.2) always features a *main chain*, in which no two blocks ever have the same *height*. Availability means that once an observer observes a main chain block at a height, that block remains available for download indefinitely.

6.1 Separating Availability and Integrity

With few exceptions [47], existing blockchain systems require that all integrity servers (e.g., miners, and consensus nodes) store all the blockchain data. This is fundamentally inefficient. For example, a traditional byzantine consensus system tolerating f failures needs $> 3f$ participants, while a storage system tolerating f failures needs only $> f$ participants. If blockchain systems separated storage and consensus duties, they would be able to store about 3 times as much as they do, with the same failure assumptions.

Charlotte makes it easy to separate availability from integrity. Wilbur servers store blocks, and provide availability attestations (§4.1). References to those blocks carry those attestations, proving the block referenced is available. Fern servers need only issue integrity attestations for each block on the chain, rather than storing it themselves.

For example, if one were to build something like Ethereum in Charlotte, what Ethereum calls *block headers* would themselves be integrity attestations, and the Merkle root in each would instead be a reference (or collection of references) to blocks stored on Wilbur servers. This makes it natural to search and retrieve block headers and portions of state, without splitting apart blocks, or downloading the whole chain.

6.2 Integrity Mechanisms

Different blockchains have used a variety of mechanisms to maintain the integrity of the chain [51, 46, 8]. To demonstrate the flexibility of Charlotte, we have implemented a few example mechanisms in small-scale experiments.

6.2.1 Nakamoto (Proof-or-Work)

We can represent a Bitcoin/ Ethereum style blockchain as an ADDS D whose states are trees of proof-of-work blocks. An observer with security parameter k (say, 6) believes only in universes with a main chain that grows faster than any side chains differing by k or more blocks. More precisely, if a universe U includes a state S of such a blockchain D featuring a fork of k or more blocks, one side of the fork must be the *main* chain, and all main chain blocks k or higher above the root of the fork must be observed before ($\overline{\sqsubseteq}$) all other blocks in S of equal height.

6.2.2 Agreement

Some blockchain applications only require agreement: they lose liveness if two *potentially* valid blocks are proposed for the same height [57, 42, 63]. For instance, if a chain represents a single bank account, and potentially valid blocks represent transactions signed by the account holder, then honest account holders should never sign two transactions unordered by the blockweb.

Agreement servers are simple to implement. When a server attests to a block, it promises never to attest to any conflicting block. For a given server, an agreement attestation type τ does not feature any universes where two conflicting blocks both have an attestation from the server. Observers can construct quorums of trusted servers, as in §3.8. A block appears in an observer’s view when the observer has observed enough attestations: committing a conflicting block would require too many parties to break their promises.

6.2.3 Heterogeneous Consensus (Hetcons)

is our own consensus algorithm based on Leslie Lamport’s Byzantine Paxos [40]. Hetcons allows each pair of observers (*learners* [40]) to specify the set of universes (§3.2) in which they must agree. They define these universes in terms of which Fern servers (*acceptors* [40]) are *safe* (not Byzantine) and *live* (not crashed) in each. In this way, we support heterogeneous servers, heterogeneous (or “mixed” [58]) failure models, and heterogeneous observers. In the symmetric case, when all observers have the same failure tolerances, Hetcons reduces to regular Byzantine Paxos [40].

For each observer, Hetcons forms quorums of participants whose attestations are necessary to put a block in the observer’s view. Generally speaking, two observers will agree so long as all their quorums intersect on a safe participant.

6.3 Blocks on Multiple Chains

In general, nothing prevents a single block from being part of multiple chains. It simply requires the integrity attestations for each chain. For example, if one blockchain represents records of events that have happened to a specific vehicle (crashes, repairs, ...), and another represents repairs a specific vendor has performed, it makes sense to append the record of a specific repair to both chains. The record (a block) could reference the previous blocks on each chain, and the next blocks on each would in turn reference it. Each chain’s integrity mechanism would have to attest to the block, and references to the block could carry both sets of attestations to let readers know it is in both ADDSs.

6.3.1 Atomicity

Sometimes, such block appends need *atomicity*. For example, suppose one blockchain represents the cryptocurrency **RedCoin**, and another represents the cryptocurrency **BlueCoin**. ALICE wants to give BOB one **RedCoin** in exchange for one **BlueCoin**. This represents two transactions: one on each chain. Crucially, either *both* happen, or *neither* do. Otherwise, it's possible that ALICE will give BOB a **RedCoin**, and get nothing in return. We want to commit both transactions together, *atomically*.

6.3.2 Meet

To atomically commit one block to multiple ADDSs, we require a single integrity attestation which represents a commitment to all of them. We call the type of this integrity attestation the *meet* (\sqcap) of the types of the integrity attestations for the ADDSs involved. If an attestation of type τ_r commits a block to **RedCoin**, and an attestation of type τ_b commits a block to **BlueCoin**, then an attestation of type $\tau_r \sqcap \tau_b$ commits a block to both. In a sense, $\tau_r \sqcap \tau_b$ is a subtype of τ_r or τ_b , since an attestation of the meet type can be used wherever an attestation of either supertype can. In our types-as-observers semantics (§3.7), we define meet as $\sqcap \triangleq \sqcap$. The assumptions made by the meet type encapsulate all the assumptions made by its component types.

Not all pairs of integrity attestation types have a meet. However, we created meet types for our Hetcons blockchains. The quorum necessary for an attestation with the meet type is the union of one quorum from each component type. In other words, to make an observer decide with an integrity attestation of type $\tau_r \sqcap \tau_b$, you need all the participants it would take to make an attestation of type τ_r *and* all the participants it would take to make an attestation of type τ_b . With this construction, we can atomically commit a single block onto multiple Hetcons chains.

6.4 Linearizable Transactions on Objects

It can be useful to model state as a collection of stateful *objects*, each of which has some availability and integrity constraints [56]. We can model objects as a chain of blocks, defined by availability and integrity attestations upholding these constraints. For instance, if an object must be consistent and available so long as 3 of a specific 4 servers are correct, each block should have “store forever” availability attestations from 2 servers, and integrity attestations from 3 stating that they’ll never attest to any other block in that slot.

Each block represents a state change for each of the objects represented by chains of which the block is a part. In other words, the blocks are *atomic* (or *ACID*) *transactions* in the database sense [26]. A collection transactions is guaranteed to have a consistent, serial order so long as the chains maintained for each of the objects they touch are consistent. For a given observer, the transactions involving objects which that observer assumes to be linearizable have a serial order so long as that observer’s assumptions are correct. Furthermore, two correct observers can never see two transactions oppositely ordered.

This gives programmers a natural model for atomic transactions across object-chains with different integrity and availability mechanisms, which would be useful for applications from banking to supply chain tracking. Transactions can involve any set of objects, so long as their integrity mechanisms have a meet operation for atomic commitment (§6.3).

| | | Unaltered | 2 Accounts |
|--------------|---------------|-------------------|-------------------|
| linearized | longest chain | 6,953,512 | 24,129,215 |
| | time | 3.72 years | 12.91 years |
| parallelized | longest chain | 110,787 | 244,163 |
| | time | 21.63 days | 47.68 days |

Figure 11: Theoretical advantages of Charlotte-style parallelization in the Bitcoin payment network

6.4.1 Banking

We can imagine bank accounts as a linearizable objects, with state changes being deposits and withdrawals to and from other bank accounts, signed by appropriate parties. We can model this in Charlotte. Each bank maintains some integrity mechanism (Fern servers) to ensure accounts’ state changes are totally ordered, which prevents double-spending. Likewise, each bank maintains some Availability mechanism (Wilbur servers), ensuring transactions relevant to their customers’ accounts aren’t forgotten. Each transaction is thus a block shared by two chains, and must be committed atomically onto both chains.

When considering how “trustworthy” the money in an account is, what matters is the integrity of the ADDS featuring the full ancestry of all transactions in the account. To ensure the trustworthiness of their accounts, banks may issue their own integrity attestations for all transactions in the causal past of transactions involving that bank. This requires checking that ancestry for any inconsistencies with anything to which the bank has already attested. This ensures any observers trusting the bank’s attestations have consistent view (§3.2), but cannot guarantee that observers trusting different banks have the same view.

An “attest to the complete history” approach is analogous to auditing the full finances of everyone with whom you do business for every transaction. In reality, much of the time, banks effectively trust each other’s attestations. This allows much faster transaction times with weaker guarantees.

6.4.2 Supply Chain Tracking

Much like bank accounts, we can imagine each good in a supply chain as a linearizable object. Transactions may involve decreasing / destroying some goods to increase / create others. For example, a transaction might feature destroying 10 kg from a case of grapes to add 9 kg to a vat of juice, and 1 kg to a bin of compost. As with banking, each good is only as “trustworthy” as the ADDS featuring its complete ancestry, and audits / attesting to past transactions can increase this trustworthiness.

6.5 Application to Payment Graphs

The Charlotte framework makes it easy to imagine parallelized blockchain-based payments, with each account as a stateful object, represented by a chain (§6.4.1). As the Bitcoin payment network is a popular example of blockchain-based finance, we consider the theoretical advantages offered by parallelization in a Charlotte-style approach.

Bitcoin does not keep track of money in terms of accounts. Instead, each transaction divides all its money into a number of outputs, called Unspent Transaction Outputs,

or UTXOs, each of which specify the conditions under which they can be spent (e.g., a signature matching this public key). Each transaction specifies a set of input UTXOs as well, from which it gets the money, and it provides for each a proof that it is authorized to spend the money (e.g., a digital signature). Each UTXO is completely drained when it is spent, and cannot be reused. Thus, Bitcoin transactions form a graph, with transactions as vertices and UTXOs as directed edges [51].

In our Charlotte banking model, each bank account is a chain, so a transfer between two accounts is simply a block on two chains (§6.4). Therefore, if two sets of financial transactions don’t interact, they can operate entirely in parallel. The speed of the system is limited by the speed of its slowest chain. If appending a transaction to its chains takes constant time, the speed limit is simply the length of the longest chain.

Blocks 1 through 200,000 of Bitcoin contain 6,953,512 transactions. The longest chain through this graph has length 110,787, so in principle, Charlotte needs time for only 110,787 rounds of consensus to accommodate the entire payment graph. Although Bitcoin batches several transactions per block, it required 200,000 rounds of consensus to do the same, taking a total of 3.72 years. Thus, even with a similarly slow consensus mechanism, a parallelized Charlotte approach, even with no batching, would require only 21.63 days. Of course, Charlotte bank accounts can specify Fern servers with whatever consensus mechanism they like. This could be a much faster system, such as PBFT [10].

In Bitcoin, it improves anonymity and performance to combine many small transfers of money into big ones, with many inputs and many outputs. In the real financial system of the USA, however, all monetary transfers are from one account to another. They are all exactly two-chain transactions. We can simulate this limitation by refactoring each transaction as a DAG of transactions with logarithmic depth (Appendix A).

With this construction, a Charlotte banking system might use more than one transaction per Bitcoin transaction. The longest chain through this new transaction graph has length 244,163; so, in principle, Charlotte can process the entire graph in only this many rounds of consensus. Thus, even with a consensus mechanism as slow as that of Bitcoin, Charlotte would still require only 47.68 days, a speedup of 28.

7 Implementation

Our full Charlotte spec, with all example types and APIs, is 298 lines of gRPC (mainly protobuf) [25]. We implemented proof-of-concept servers in 3833 lines of Java [24] (excluding comments and import statements), with a further 1133 lines of unit tests. We also wrote 1149 additional lines of Java setting up various experiments. Anonymized code is available [2].

7.1 Wilbur servers

By default, our example Wilbur servers store all blocks received in memory forever. They are not meant to be optimal, but they are usable for proof-of-concept applications. The only type of availability attestation we have implemented is one in which the Wilbur servers promise to store the block indefinitely. This attestation proves that the block is available as long as the Wilbur server is functioning correctly.

Our Wilbur servers can be configured with a list of known peers, to whom they will relay any blocks they receive and any attestations they create. This is easy to override: servers can be made to relay blocks to any collection of peers.

```

1 message PublicKey {
2   message EllipticCurveP256 {
3     bytes byteString;
4     oneof keyalgorithm_oneof {
5       AnyWithReference any;
6       EllipticCurveP256 ellipticCurveP256;}}
7   message CryptoId {
8     oneof idtype_oneof {
9       AnyWithReference any;
10      PublicKey publicKey;
11      Hash hash;}}
12  message Signature {
13    message SHA256WithECDSA {
14      bytes byteString;}
15    CryptoId cryptoId;
16    oneof signaturealgorithm_oneof {
17      AnyWithReference any;
18      SHA256WithECDSA sha256WithEcDSA;}}

```

Figure 12: Signature Specification. We include Any types for extensibility, as well as default built-in types, like Sha256WithECDSA. Note that the `message` keyword defines a type in the local scope.

We also implemented the WilburQuery service of §5.1.1. Our Wilbur servers can do fill-in-the-blank pattern matching on all implemented block types. The Wilbur Query service imposes no overhead on other services.

7.2 Version Control

We implemented a simulation of Git [68]. Our servers are not fully-functional version control software, as they do not implement file-diffs and associated checks, which are irrelevant for the purpose of demonstrating the Charlotte framework.

The types for our version control ADDS are described in Figure 13. We created a block subtype, `SignedGitCommit`, representing a specific state of the files tracked. Each block features a signature, comment, hash of the state. It can be an *initial* commit, in which case it has no parents, but does include bytes representing the full contents of the files being tracked. Alternatively, it can have some number of parent commits, each with a reference and a file diff.

A Version Control Fern server tracks the current commit it associates with each *branch* (strings). They issue integrity attestations that declare which commits they've put on which branches. A correct Fern server should never issue two such attestations for the same branch, unless the commits they reference are ordered by the blockweb. In other words, each new commit on a branch should follow from the earlier commit on that branch; it cannot be an arbitrary jump to some other files. Our example servers enforce this invariant [2].

Fern servers can have other reasons to reject a request to put a commit on a branch. Perhaps they accept only commits signed by certain keys. When a client issues a request, they can include attestation references. A Fern server can demand that clients prove a commit is, for instance, stored on certain Wilbur servers before it agrees to put it on a branch. The Wilbur servers need not even be aware of the Git data types.

```

1 message SignedGitSimCommit {
2     message GitSimCommit {
3         message GitSimParents {
4             message GitSimParent {
5                 Reference parentCommit;
6                 bytes diff;}
7             repeated GitSimParent parent; }
8             string comment;
9             Hash hash;
10            oneof commit_oneof {
11                bytes initialCommit;
12                GitSimParents parents;}}
13            GitSimCommit commit;
14            Signature signature; }
15
16 message Block {
17     oneof blocktype_oneof {
18         AnyWithReference any;
19         string protobuf;
20         SignedGitSimCommit signedGitSimCommit;}}
21
22 message IntegrityAttestation {
23     message GitSimBranch {
24         google.protobuf.Timestamp timestamp;
25         string branchName;
26         Reference commit; }
27     message SignedGitSimBranch {
28         GitSimBranch gitSimBranch;
29         Signature signature; }
30     oneof integrityattestationtype_oneof {
31         AnyWithReference any;
32         SignedGitSimBranch signedGitSimBranch;}}

```

Figure 13: Git Simulation integrity attestation Specification. We include Any types for extensibility, and provide types like SignedGitSimBranch as options. Note that the `message` keyword defines a type in the local scope, and that the `Signature` type is defined in the full Charlotte spec [2].

Our version control implementation can use the same Wilbur servers as any other application. In fact, separating out the storage duties of Wilbur from the branch-maintaining duties of Fern allows our Charlotte-Git system to divide up storage duties of large repositories, much like git-lfs [22].

7.3 Timestamping

Timestamps are a subtype of integrity attestation. Each Timestamp includes a collection of references to earlier blocks, the current clock time [33], and a cryptographic signature.

Our Timestamping Fern servers timestamp any references requested, using the native OS clock. By default, they issue a timestamp immediately for any request, and do not need to actually receive the blocks referenced. Because references contain hashes, the request itself guarantees the block’s existence before that time.

```

1 message IntegrityAttestation {
2     message TimestampedReferences {
3         google.protobuf.Timestamp timestamp;
4         repeated Reference block;
5     }
6     message SignedTimestampedReferences {
7         TimestampedReferences timestampedReferences;
8         Signature signature;
9     }
10    oneof integrityattestationtype_oneof {
11        AnyWithReference any;
12        SignedTimestampedReferences sigTimeRefs;
13    }
14 }
```

Figure 14: Timestamping integrity attestation Specification. We include Any types for extensibility, and provide SignedTimestampedReferences as an option. Note that the `message` keyword defines a type in the local scope, and that the `Signature` type is defined in the full Charlotte spec [2].

Our Timestamping Fern servers also implement *batching*. Every 100 (configurable at startup) timestamps, the Fern server issues a new timestamp, referencing the blocks it has timestamped since the last batch. Each server then submits its batch timestamp to other Fern servers (configurable at startup) for timestamping. Since timestamps are transitive (if a timestamps b , and b references c , then a also timestamps c), blocks are very quickly timestamped by large numbers of Fern servers. This allows applications to quickly gather very strong timestamp integrity.

7.4 Blockchains

In principle, any path through the blockweb is a blockchain (§6). We implemented Fern servers using three very different integrity mechanisms (§6.2). We used some of these servers to demonstrate the advantages of separating integrity and availability mechanisms (§6.1), and blockchain composition: we put blocks on multiple chains (§6.3).

7.4.1 Agreement

Our Agreement Fern servers keep track of each a blockchain as a *root* block, and a set of *slots*. Each slot has a number representing distance from the root of the chain.

Our Agreement Fern servers use the `SignedChainSlot` subtype of integrity attestation (Figure 15). It features a cryptographic signature, and references to a chain’s *root*, a slot number, and the block in that slot. This serves as a format for both requests and attestations. Each request is simply an `IntegrityAttestation` with some fields (like the cryptographic signature) missing. While it is possible to encode this in the `IntegrityPolicy`’s `any` field, we provide the `fillInTheBlank` option as a convenience.

The Agreement Fern servers are configured with parameters describing which requests they can accept, in terms of requirements on the reference to the proposed block and its parent. Once a correct Agreement Fern server has attested that a block is in a slot, it will *never* attest that a different block is in that slot. For instance, to configure a blockchain using quorums of 3 Agreement Fern to approve each block, we require that each request’s parent Reference include 3 appropriate integrity attestations.

```

1 message IntegrityAttestation {
2     message ChainSlot {
3         Reference block;
4         Reference root;
5         uint64 slot;
6         Reference parent;}
7     message SignedChainSlot {
8         ChainSlot chainSlot;
9         Signature signature;}
10    oneof integrityattestationtype_oneof {
11        AnyWithReference any;
12        SignedChainSlot signedChainSlot;}}
13 message IntegrityPolicy {
14     oneof integritypolicytype_oneof
15     { AnyWithReference any;
16       IntegrityAttestation fillInTheBlank;}}

```

Figure 15: Agreement integrity attestation Specification. We include Any types for extensibility, and provide SignedChainSlot as an option. Note that the `message` keyword defines a type in the local scope, and that the `Signature` type is defined in the full Charlotte spec [2].

Our Agreement Fern servers make it easy to separate integrity and Availability duties (§6.1). To ensure that a block is available before committing it to the chain, we require a block Reference to include specific availability attestations from Wilbur servers.

7.4.2 Nakamoto

Nakamoto, or *Proof of Work* Consensus is the integrity mechanism securing Bitcoin [51]. We model it formally in §6.2.1. In Bitcoin, *miners* create proofs of work, which are stored by *full nodes*. With the Simplified Payment Verification (SPV) protocol, *clients* submit a transaction, and retrieve the *block headers* (proofs of work and Merkle roots) of each block in the chain from full nodes [51]. Each client can use these to verify that

```

1 message IntegrityAttestation {
2     message NakamotoIntegrityInfo {
3         Reference block;
4         Reference parent;}
5     message NakamotoIntegrity {
6         NakamotoIntegrityInfo info;
7         uint64 nonce;}
8     oneof integrityattestationtype_oneof {
9         AnyWithReference any;
10        NakamotoIntegrity nakamotoIntegrity;}}

```

Figure 16: Nakamoto integrity attestation Specification. We include Any types for extensibility, and provide NakamotoIntegrity as an option. Note that the `message` keyword defines a type in the local scope. [2].

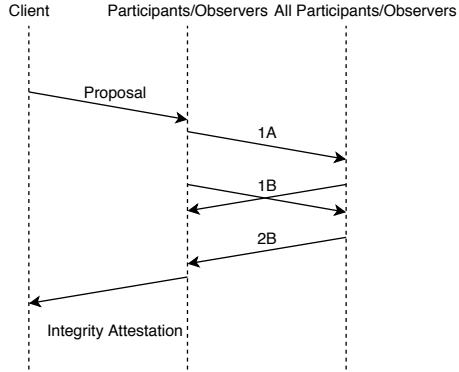


Figure 17: Heterogeneous Consensus Message Latency

its transaction is in the chain (has integrity).

We implement miners as Fern servers, which produce integrity attestations bearing proofs of work, taking the place of block headers. Wilbur servers take the place of full nodes, and store blocks, including integrity attestations. For simplicity, our implementation assumes one transaction per block, so clients generate blocks, and request attestations. When a client receives an integrity attestation (Figure 16), it can retrieve the full chain from Wilbur servers.

With SPV, Clients traditionally try to collect block headers until they see their transactions buried “sufficiently deep” in the chain. For simplicity, our Fern servers delay responding to the client at all until the client’s block has reached a specified (configurable) depth. Regardless, clients can collect integrity attestations from Wilbur servers until they’re satisfied.

Our implementation of Nakamoto consensus offers a more precise availability guarantee than Bitcoin does. Nakamoto Fern servers demand availability attestations with any blocks submitted, ensuring that before a block is added to the chain, it meets a (configurable) availability requirement.

7.4.3 Heterogeneous Consensus

We implemented a prototype of Hetcons (§6.2.3) as a Fern service. Integrity attestations are specific to each observer’s assumptions. We use Charlotte blocks as messages in the consensus protocol itself, so attestations can reference messages demonstrating that consensus was achieved.

Hetcons inherits Byzantine Paxos’ minimum latency of 3 message delays. In our implementation, clients do not participate in the consensus: they merely request an integrity attestation from a Fern server. Including receiving a request from and sending an attestation to the client, the process has a minimum latency of 5 messages (Figure 17).

In our implementation, quorums representing trust configurations are encoded as blocks. Each Hetcons blockchain includes a reference to such a block in its root, ensuring everyone agrees on the configuration. To append a block to the chain, a client requests an integrity attestation for some observer, specifying proposed block and height. To propose one block be appended to multiple chains, a client can request an integrity attestation that is the meet (§6.3) of the integrity attestations needed for both chains.

The Fern servers then run a round of consensus in which each quorum includes one quorum of the consensus necessary for each chain.

For the purposes of demonstrating the Charlotte framework, our experiments with Hetcons are *symmetric*: all observers want to agree under the same conditions. For instance, observers might trust 4 Fern servers to maintain a chain, expecting no more than one of them to be Byzantine.

8 Evaluation

To evaluate the performance of Charlotte, we ran instances of each example application. Except as specified, experiments were run on a local cluster using virtual machines with Intel E5-2690 2.9 GHz CPUs, configured as follows:

- Clients: 4 physical cores, 16 GB RAM
- Wilbur servers: 1 physical core, 8 GB RAM
- Fern servers: 1 physical core, 4 GB RAM

To emulate wide area communication, we introduced 100 milliseconds artificial communication latency between VMs.

8.1 Blockchains

Since blockchains are an obvious application of Charlotte, we evaluated the performance, scalability, and compositionality of various blockchain implementations.

8.1.1 Nakamoto

To compare performance of our Nakamoto implementation to Bitcoin’s, we used multiple ($n = 10, 20, 30, 40$) Charlotte nodes and measured the mean delay (across 100 consecutive blocks) until a client received an integrity attestation for a block with fixed security parameter $k = 1$. All clients and servers had one physical core, and 4 GB RAM. Figure 18 shows the results of our tests with various difficulty values (expected number of hashes to mine a block).

When difficulty is low, the delay for an integrity attestation is dominated by the communication overhead (200 ms). When, more realistically, the difficulty is high, delay is dominated by the cost of mining. Figure 18 shows that latency increases with difficulty and decreases with the inverse of the number of Charlotte servers (total computational power). Charlotte indeed scales suitably for blockchain implementations.

In fact, Bitcoin has about 2×10^{11} times the hash power [16], and 10^{14} times the difficulty as we had in our experiment, and it achieves an average block latency of 10 min. With compute power scaled appropriately, our implementation would achieve comparable performance: about 5 minutes per block.

8.1.2 Agreement

To evaluate the bandwidth advantages of separating integrity and availability services, we built Agreement Chains (§7.4.1) tolerating 1–5 Byzantine failures, both with and

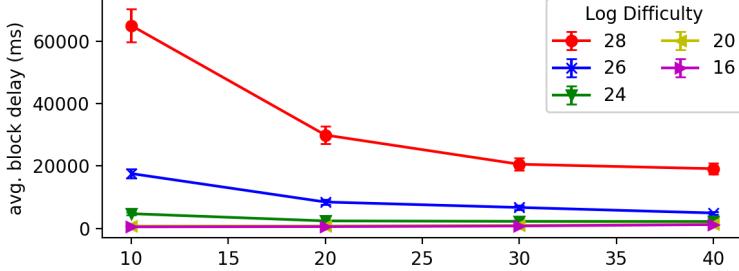


Figure 18: Mean block delay of Nakamoto on Charlotte, with bars showing standard error. Difficulty is represented in \log_2 of the number of hashes expected to mine a new block.

without Wilbur servers. To tolerate f Byzantine failures, a chain needs $3f + 1$ Fern servers, and, if it relies on Wilbur servers for availability, $f + 1$ Wilbur servers. We tested the latency and bandwidth of our chains, with some experiments using 10 byte blocks, and some using 1 MB blocks. In each experiment, a single client appends 1000 blocks to a chain, with the first 500 excluded from measurements to avoid warm-up effects. Each experiment ran three times.

In the simple case, without Wilbur servers, all Fern servers receive all blocks. This resembles the traditional blockchain strategy [51]. The theoretical minimum latency is 2 round trips from the client to the Fern servers, or 200 ms.

We also built chains that separate the Fern servers' integrity duties from Wilbur servers' availability duties. In these chains, Fern servers would not attest to any reference unless it included $f + 1$ different Wilbur servers' availability attestations.

Latency

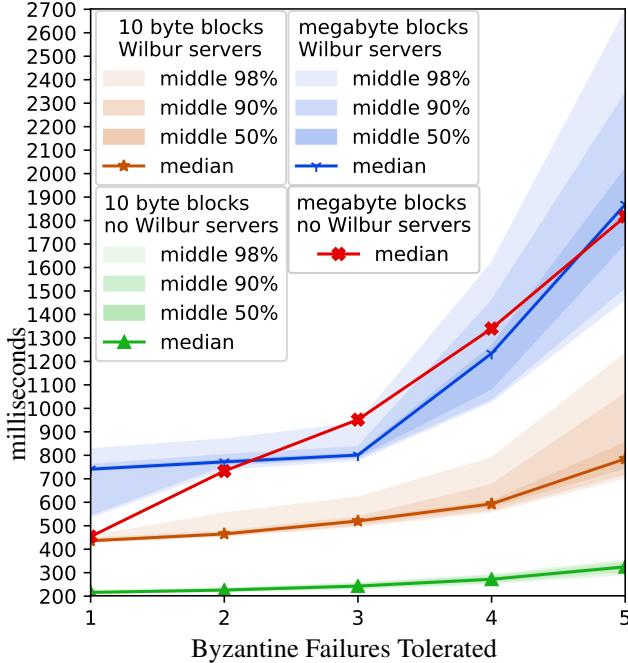


Figure 19: Time to commit blocks in Agreement chains with various numbers of servers. The shaded zones cover the middle percentile of blocks, so the top of the lightest zone represents the 99th (slowest) percentile, and the bottom represents the 1st (fastest) percentile. The distribution for the megabyte-block, no-wilbur-server experiment is in Figure 20.

Figure 19 and Figure 20 show the median latency to commit a block for each of our Agreement chain experiments. Theoretical minimum latency is 4 message sends (round trip from the client to the Wilbur servers, and then from the client to the Fern servers), or 400 ms. For chains with small blocks, latency remains close to the 200 ms and 400 ms minimums. For chains with 1 megabyte blocks, experimental setup has significant slowdowns, likely due to bandwidth limitations.

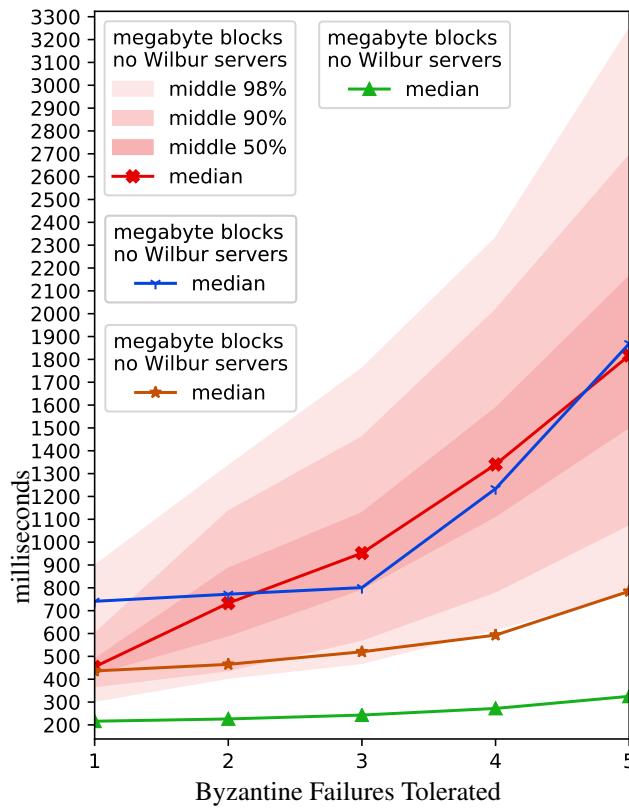


Figure 20: Time to commit blocks in Agreement chains with various numbers of servers. The distribution for the megabyte-block, no-wilbur-server experiment is shown.

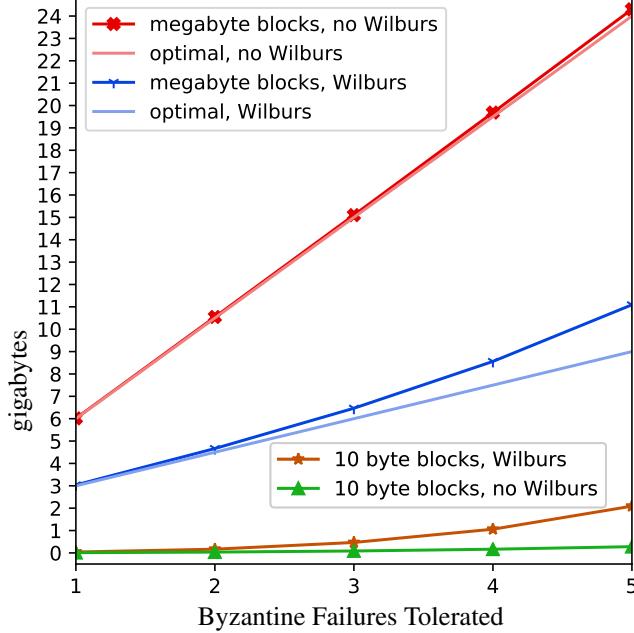


Figure 21: Total bandwidth used by a client appending 1500 blocks to Agreement-based chains.

Bandwidth Separating availability and integrity concerns (§6.1) has clear benefits in terms of bandwidth. Because it sends large blocks to just $f + 1$ Wilbur servers instead of $3f + 1$ Fern servers, our client uses much less bandwidth in the large-block experiments with Wilbur servers than without them (Figure 21). In theory, committing a block with Wilbur servers requires bandwidth for $f + 1$ blocks, and without Wilbur servers requires $3f + 1$ blocks. The overhead inherent in the additional communication with Wilbur servers and the attestations issued is small compared to the savings.

8.1.3 Heterogeneous Consensus

In order to evaluate the feasibility of consensus-based blockchains, and multi-chain blocks in Charlotte, we built several chains with Hetcons (§6.2.3), and ran 5 types of experiments. With our artificial network latency, the theoretical lower bound on consensus latency is 500 ms, and maximum throughput per chain is 2 blocks/second. Each experiment recorded the latency clients experience in appending their own blocks to the chain, as well as system-wide throughput. All Hetcons experiments used single-core VMs with 8 GB RAM, except as noted.

Single Chain In these experiments, a client appends 2000 successive blocks to one chain. Mean latency is 527ms for a chain with 4 Fern servers and 538ms for 7 Fern servers. Since the best possible is 500 ms, these results are promising. Overheads include cryptographic signatures, verification, and garbage collection.

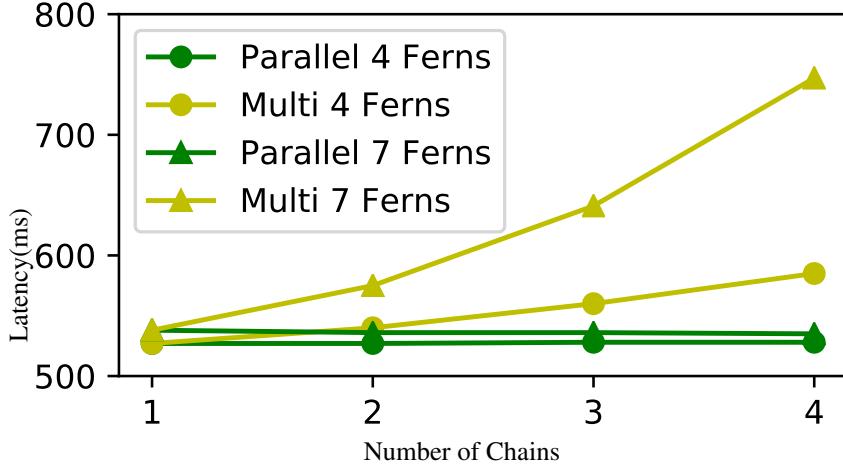


Figure 22: Hetcons Multichain and Parallel experiments. In Parallel experiments, each chain operates independently (and has its own client). In Multichain experiments, one client tries to append all blocks to all chains. Optimal latency is 500 ms.

Parallel As the darker green lines in Figure 22 show, independent Hetcons chains have independent performance. In these experiments, we simultaneously ran 1–4 independent chains, each with 4 or 7 Fern servers. In each experiment, a client appends 2000 successive blocks to one chain. There is no noticeable latency difference between a single chain and many chains running together. Throughput scales with the number of chains (and inversely to latency). This scalability is the fundamental advantage of a blockweb over forcing everything onto one central blockchain.

Multichain shared blocks Shared (joint) blocks facilitate inter-chain interaction (§6.3). In these experiments, a single client appends 1000 shared blocks to 2–4 chains, each with 4 or 7 Fern servers. As the yellow lines in Figure 22 show, latency scales roughly linearly with the number of chains.

Contention In these experiments, all clients simultaneously contend to append 2000 unique blocks to the same chain. We measured the blocks that were actually accepted into slots 500–1500 of the chain. We used 2–36 clients, and chains with 4 or 7 Fern servers, configured with 2 GB RAM. Like Byzantized Paxos [40], Hetcons can get stuck under contention and occasionally requires a dynamic timeout to automatically trigger a new round. Chain throughput is shown in Figure 23. Our chains, on average, achieved 1.88 blocks/sec throughput for 4 Fern servers and 1.85 blocks/sec for 7, not far from the 2 blocks/sec optimum. Throughput does not decrease much with the number of clients.

Mixed These experiments attempt to simulate a more realistic scenario by including all 3 types of workload. 2–5 clients contend to append blocks onto either 2 or 7 chains, each with 4 Fern servers. On each block, a client tries to append a shared block to two random chains with probability 10% and otherwise tries appending to a random single

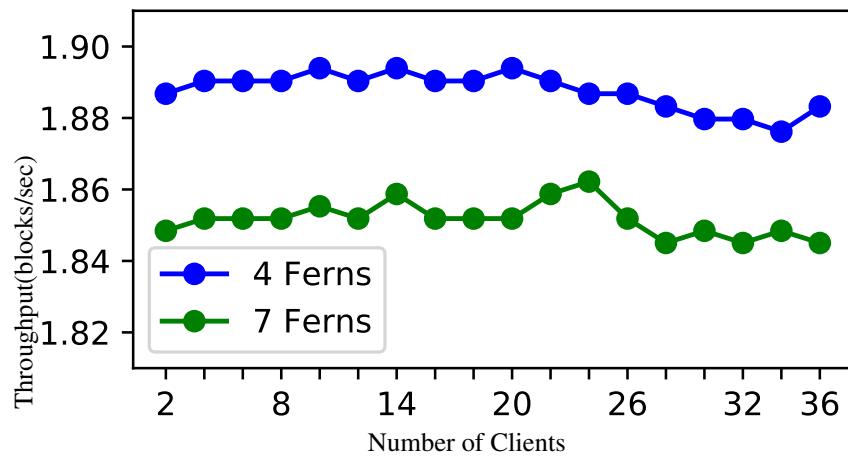


Figure 23: Throughput of Hetcons under contention. 2–36 clients try to append 2000 blocks to just one chain. Optimal throughput is 2 blocks/sec.

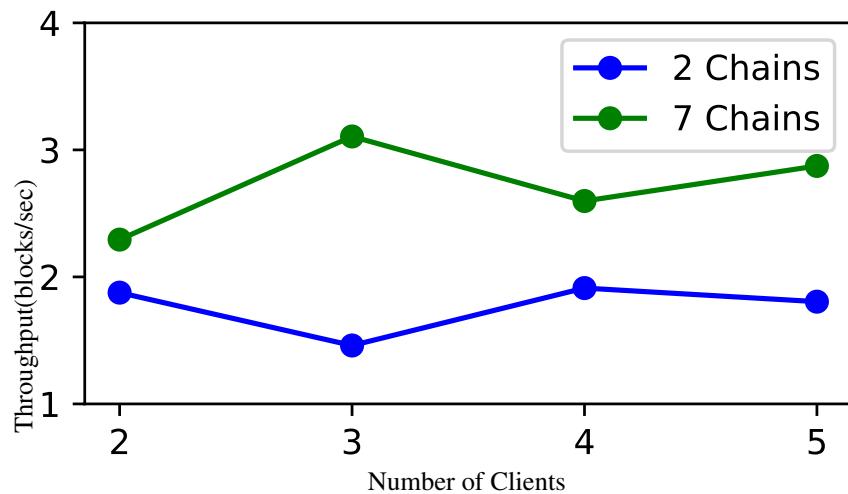


Figure 24: Throughput of Hetcons mixed-workload experiment (4 Fern servers).

chain. The results are in Figure 24. Throughput can be over 2.0 blocks/sec because multiple clients can append blocks to different chains in parallel. Mean throughput is 1.8 blocks/sec and 2.7 blocks/sec for 2 and 7 chains respectively, which is expected because the 2-chain configuration has more contention.

Hetcons scales well horizontally with multiple chains running in parallel. Furthermore, throughput does not decrease much with more clients involved.

This gives us ability to make progress even with lots of clients connecting to the same chain concurrently. We also notice that, the number of Ferns servers play major roles for the latency performance. With a small group of Fern servers, Hetcons can almost reach 500 ms, which is the best we can get. Although the latency increases linearly with respect to the number of Ferns, for some applications, it is possible to break down big shared blocks into a set of small shared blocks. For example, in §6.5, we discuss how to break a k -chain transaction into a log k -depth graph whose nodes are small two-chain transactions. By following the same strategy, the latency would be reduced to $t \times \log k$, where t is the average latency for completing a 2-chain block. Since our Hetcons implementation is just a prototype, we believe that with further efforts in optimization, average latency performance can be improved.

8.2 Timestamping

To evaluate performance, compositionality, and entanglement (§5.5) with a non-blockchain application, we ran experiments with varying numbers of Timestamping Fern servers (§7.3). All client and server VMs had 4 GB RAM. For each experiment, a single client requested timestamps for a total of 100,000 blocks. For each block, it requested a timestamp from one server, rotating through the Fern servers.

For each 100 timestamps a Fern server issued, it would create a new block referencing those 100 timestamps, and request that all other Fern servers timestamp this block. Since timestamps are transitive (if c is a timestamp referencing b , and b references a , then c also timestamps a), every block was soon timestamped by all Fern servers.

To explore Charlotte’s compositionality, we also composed our (1- or 2-failure-tolerant) Agreement chains with our Timestamping Fern servers. We saw no statistically significant change in chain performance: the overhead of Timestamping was unmeasurably small. Each block was timestamped quickly by directly requested Timestamping servers, but entanglement (§8.2) was limited by the chain rate.

We also calculated the time it took blocks to accrue different Fern servers’ timestamps. As Figure 25 shows, the Fern servers quickly timestamp each request. Blocks get 1 timestamp very close to the 100 ms network latency minimum. There is a delay between 1 and 2 timestamps because it takes a little while for the Fern servers to collect 100 timestamps and to create their own block. After that, blocks accrue timestamps very quickly, since each Fern Server requests timestamps from all other Fern servers. These experiments suggest that entanglement (§5.5) can be a fast, efficient, and compositional way to lend integrity to large ADDSs.

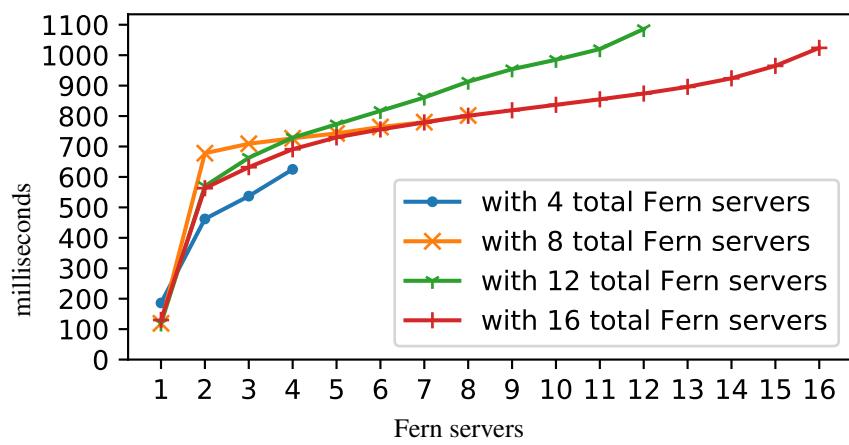


Figure 25: Mean time for a block to be timestamped by x Fern servers, in experiments featuring 4, 8, 12, and 16 total Fern servers.

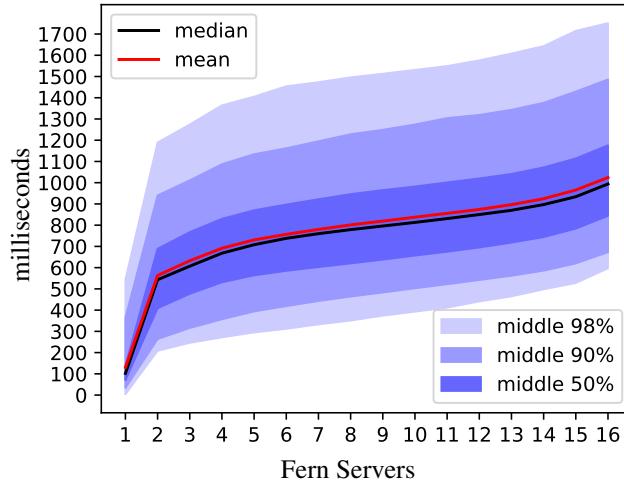


Figure 26: Time for a block to be timestamped by x Fern Servers, in an experiment featuring a total of 16 Fern Servers. Shaded zones cover the middle percentile of blocks, so the top of the lightest zone represents the 99th (slowest) percentile, and the bottom represents the 1st (fastest) percentile. Also shown are mean and median block times (very similar).

Not all blocks took exactly the same amount of time to accrue the same number of timestamps. Figure 26 shows the distribution of times for blocks in the experiment with 16 Fern Servers. The scale is the same as in Figure 25. In general, each data point (time for blocks to accrue x timestamps in an experiment with n Fern Servers) was approximately Poisson distributed.

9 Related Work

9.1 Address by Hash

Many other distributed systems reference content by hash, forming ADDSs. Most reference schemes, however, only work within a specific application. For instance, git uses hashes to reference and request commits stored on a server [68]. Git-lfs can track and request large files on separate servers with hash-based identifiers [22]. Similarly, PKI systems (§2.7) reference keys and certificates by hash, and maintain groups of availability servers [31, 28, 38]. Distributed Hash Tables, such as CFS [14] ultimately maintain Availability servers, and ensure integrity by referencing data via Hash.

HTML pages can reference resources using the `integrity` field [70] to specify a hash, and the `src` field to specify a server, like an availability attestation without formal guarantees. Likewise, BitTorrent’s Torrent files [12] and Magnet URIs [13] reference a file by hashes of various kinds, and can specify “acceptable sources” from which to download the file. Charlotte’s references aim to be extensible in terms of the hash algorithms used, and generic over all types of data. Uniquely, Charlotte bundles references to data with references to attestations, which can offer precise formal guarantees.

In concurrent work, Protocol Labs’ IPLD [35] is a multi-protocol format for addressing arbitrary content by hash. Like Charlotte’s `AnyWithReference` (§4), Multiformats [50] offers an extensible format for self-describing data including protobufs [55]. Both IPLD and Multiformats are developed closely with IPFS [4], a peer-to-peer file distribution system. IPLD references do not include attestation references the way Charlotte references do, but future work could fruitfully combine these technologies with Charlotte’s reference and block encoding formats.

9.2 BlockDAGs

Other projects have explored DAGs of blocks in a blockchain context. Many, such as Iota [53], Nano (also known as RaiBlocks) [42], Avalanche [57], Spectre [63], Phantom, and Ghostdag [64] are tailored to cryptocurrency. Each defines its own currency, and they do not compose.

Some projects, such as æternity [27], alephium [69], Qubic [34], and Plasma [52] enable general-purpose computation on a BlockDAG by way of smart contracts. However, they ultimately rely on a single global consensus mechanism for the integrity of every application.

Sharded blockchains, including Omniledger [37], Elastico [44], RapidChain [72], RSCoin [15], and Ethereum 2.0 [7] are a form of BlockDAG. Most still require that all applications have essentially the same trust assumptions.

Other sharded blockchain projects, such as Aion [66], Cosmos [20], and Polkadot [71], envision heterogeneous chains with inter-chain communication. Polkadot features a single Relay Chain trusted by all parachains (parallelizable chains), although it does allow parachains to proxy for outside entities, including other blockchains. Perhaps most similarly to our multi-chain transactions (§6.3), Aion can use Bridges, consensus mechanisms trusted by multiple chains, to commit a transaction to each.

All of these blockchain projects operate at a higher level of abstraction than Charlotte. Charlotte is a generic format for communicating blocks, with a novel attestation-based model for specifying availability and integrity properties. However, we believe any of these projects could benefit from building their implementations within the Charlotte framework. For example, where Cosmos’ Inter-Blockchain Communication [20]

and Aion’s Transwarp Conduits [29] require that one chain be able to read and validate transaction commits from another, we present a unified framework for the data they must request and interpret: integrity attestations.

9.3 Availability attestations

Although storage services are widely available [1, 23, 49], availability attestations (§3.7) make Wilbur servers unique. The only type of availability attestation we have implemented is a simple promise to store a block indefinitely. However, there is a great deal of work on reliable storage [17, 21] and proofs of retrievability [36, 6, 61] that could be used to make a variety of availability attestation subtypes that provide more availability with less trust.

9.4 Integrity attestations

Integrity attestations abstract over a variety of mechanisms lending integrity to data provenance and ADDS properties. In some ways, attestations resemble the labels of distributed information flow control systems [74, 43], and implement a kind of endorsement [73] as additional attestations are minted for the same block. In other ways, integrity attestations generalize ordering services for traditional distributed systems [32] or blockchains [65]. These services maintain a specific property of a ADDS (ordering), much like our blockchain integrity attestations. However, integrity attestations generalize over many possible properties: timestamps, provenance, etc.

Future integrity attestation subtypes might take advantage of technologies like authentication logic proofs and artifacts representing assurances of data provenance [3, 62].

10 Conclusion

Charlotte offers a decentralized framework for composable Authenticated Distributed Data Structures with well-defined availability and integrity properties. Together, these structures form the blockweb, a novel generalization of blockchains. Charlotte addresses many of the shortcomings of existing ADDSs by enabling parallelism and composability. Charlotte is flexible enough to enable applications patterned after any existing ADDS while offering rigorous guarantees through attestations that can be given precise semantics.

11 Acknowledgments

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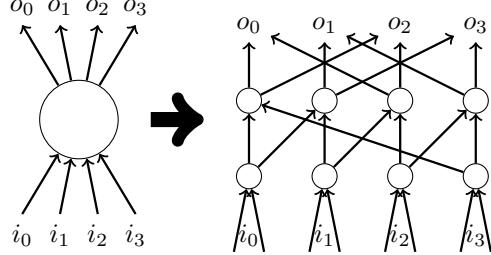


Figure 27: Converting 4 inputs and 4 outputs to a graph of 2-account transactions.

A Bitcoin Transactions in Two Accounts or Fewer

In Bitcoin, it is advantageous to combine many small transfers of money into big ones, with many inputs and many outputs. This improves anonymity and performance. In the real financial system of the USA, however, all monetary transfers are from one account to another. They are all exactly two chain transactions.

We can simulate this limitation by refactoring each Bitcoin UTXO as 2 UTXOs, and each Bitcoin transaction as a DAG of transactions with depth:

$$\lceil \log_2(\max(\text{number of inputs, number of outputs})) \rceil$$

To do this, we create

$$n \triangleq 2^d$$

chains, each of which is

$$d \triangleq \lceil \log_2(\max(\text{number of inputs, number of outputs})) \rceil$$

long. We call these chains C^0 through C^n . Original input UTXO i corresponds to both inputs to the first transaction of chain i . Original output UTXO j corresponds to one output of each of the last transactions from chains j and $(j + 2^{d-1}) \bmod n$. For $0 \leq k < (d - 1)$, the outputs of the k^{th} transaction in chain i , called C_k^i , go to C_{k+1}^i , and:

$$C_{k+1}^{(i+2^j) \bmod n}$$

The outputs of C_d^i go to the UTXOs corresponding with output i , and output $(i + 2^{d-1}) \bmod n$. Each transaction divides its output values proportionately to the sums of the final output values reachable from each of the transaction's outputs. Figure 27 is an example transformation from a 4-input, 4-output transaction to a DAG of depth 2 using all 2-input, 2-output transactions.