

CHRONO: A Peer-to-Peer Network with Verifiable Causality

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Logical clocks are a fundamental tool to establish causal ordering of events in a distributed system. They have been used as the building block in weakly consistent storage systems, causally ordered broadcast, distributed snapshots, deadlock detection, and distributed system debugging. However, prior logical clock constructs fail to work in a permissionless setting with Byzantine participants. In this work, we introduce CHRONO, a novel logical clock system that targets an open and decentralized network. CHRONO introduces a new logical clock construct, the Decaying Onion Bloom Clock (DOBC), that scales independently to the size of the network. To tolerate Byzantine behaviors, CHRONO leverages non-uniform incrementally verifiable computation (IVC) to efficiently prove and verify the construction of DOBC clocks. We have applied CHRONO to build two decentralized applications, a weakly consistent key-value store and an anti-censorship social network, demonstrating the power of scalable, verifiable causality in a decentralized network.

1 INTRODUCTION

The ordering of events is a fundamental concept in distributed systems. In state machine replication systems [17, 23, 24, 27], the set of replicas needs to agree on the order of operations in the log; shards in a distributed database [1, 9, 31] are tasked to execute distributed transactions in a consistent partial order; for mutual exclusion of shared resources, participants in a distributed system have to agree on the order of acquiring locks [5, 12, 35]; in a distributed storage system [7, 10, 11, 19, 34], servers apply a consistent order of mutations to storage objects.

It is well-known that perfectly synchronized clocks do not exist in realistic distributed systems, due to clock drift and relativity. Ordering events using physical clock timestamps is therefore not reliable and can lead to anomalies. Logical clocks [16, 28], on the other hand, offer a solution to order events in a distributed system without relying on physical time. Logical clocks are consistent with *logical causality*, *i.e.*, if event a can causally influence event b , then the logical clock of a is prior to that of b . Unlike physical time ordering, causality in a distributed system is only a partial order, as there exists events which do not causally influence each other. Many forms of logical clocks have been proposed in the literature [16, 20, 26, 28, 32], though not all of them can be used to deduce causality between events. For instance, even if an event has a smaller Lamport clock [16] than another, the two events can still be logically concurrent.

Existing logical clock constructs, however, fall short in an open, decentralized network [6, 22]. In these networks, any participant can join or leave the system at any time. Such dynamic environment presents deep scalability challenges for vector-based logical clocks [20, 28, 32]. More critically, prior systems assume all participants in the system faithfully follow the protocol to update and propagate their clocks. In a decentralized network, Byzantine [18] behaviors, where a participant can deviate arbitrarily from the specified protocol, are common. Unfortunately, existing logical clock constructs are not Byzantine-fault tolerant. By not following the clock protocol, a single Byzantine participant can easily compromise the clock's causality guarantees, *i.e.*, logical clocks may imply erroneous causality between events. Such adversaries can render the entire clock construct pointless.

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In this work, we address the above shortcomings by proposing a new logical clock system, CHRONO. CHRONO targets a permissionless network with possible Byzantine participants. Similar to prior logical clocks, CHRONO can be used to infer causality in the network. CHRONO, however, only concerns causal dependency between object states, *i.e.*, an object state is the result of a series of mutations from another object state. In return, CHRONO always infers *true causality*, unlike the possible causality implied by prior approaches. To handle dynamic membership, CHRONO introduces Decaying Onion Bloom Clock (DOBC), a novel construct based on Bloom clocks [26]. DOBC is agnostic to the identity and the number of the participants in the network. It achieves this property by applying Bloom filters to only record the state transition history. To maintain low false positive rate even for arbitrarily long causal histories, DOBC uses layers of Bloom filters, a construct inspired by log-structured merge-tree [25]. Recent transitions are stored in the top layer filters; when a layer is filled up, its filters are merged and pushed to the next layer. DOBC therefore offers accurate causality inference for recent histories, while its accuracy gracefully degrades for the distant past.

To tolerate Byzantine participants, CHRONO builds upon recent advances in verifiable computation (VC). Specifically, CHRONO applies non-uniform incrementally verifiable computation (IVC) [33], a proof system that uses recursive Succinct Non-interactive Argument of Knowledge (SNARKs) [2]. When mutating an object in CHRONO, the initiating node generates a succinct proof that demonstrates the validity of both the state transition and the DOBC clock update. The proof is attached to the object when disseminating the object in the network. A receiver verifies the attached proof before accepting the object. Using IVC, a node can incrementally mutate any verified object, and efficiently generate a succinct proof for the entire causal history of the object. Moreover, both prover time and verifier time are independent of the length of the causal history. As each node may apply arbitrary state mutation function to an object, CHRONO uses a variant of IVC called non-uniform IVC [14] to address the rigidity of the original IVC construct.

We have built two decentralized systems atop CHRONO to demonstrate the power of verifiable causality. The first system is a weakly consistent data store KSTORE. KSTORE provides eventual consistency [30] even in the presence of strong adversaries. It leverages CHRONO to track versioned histories of stored data and to effectively merge conflicting versions. It relies on provable causal history to avoid lost updates or inconsistencies caused by Byzantine behaviors. CHRONO is more scalable, available, and provides faster query latency than existing BFT systems. The second system, KSOCIAL, is an anti-censorship decentralized social network. Beyond the benefits already provided in KSTORE, CHRONO enables KSOCIAL to effectively eliminate censorship attacks, a major challenge in other social applications. Using verifiable causality, clients in KSOCIAL can enforce propagation and visibility of posted content, and generate proof-of-censorship when censorship attacks are launched.

2 BACKGROUND

This section covers background information on two main topics: causality of events in a distributed system, and verifiable computation.

2.1 Causality of Events in Distributed Systems

The seminal work by Lamport [16] introduces a *happens-before* relationship that defines the possible causality between events in a distributed system. Specifically, let \prec be a binary relation between pairs of events in an execution of a distributed system. $e_1 \prec e_2$ if event e_1 may influence event e_2 , or equivalently, e_2 is causally dependent on e_1 . \prec is a strict partial order, *i.e.*, it is *irreflexive*, *asymmetric*, and *transitive*. Being a partial order, not all pairs of events are causally dependent. If neither $e_1 \prec e_2$ nor $e_2 \prec e_1$, e_1 and e_2 are defined to be logically concurrent (represented as $e_1 \parallel e_2$).

Without perfectly synchronized physical clocks, it is impossible to determine which of e_1 or e_2 happens first if $e_1 \parallel e_2$.

Events in an execution are categorized into three general types:

- Local events on a node (e^{local}). They are any event happen on a node that does not involve messages.
- Message send event (e^{send}). A source node sends an unicast message to a destination node. Broadcasts or multicasts are equivalent to a set of unicast messages.
- Message receive event (e^{recv}). For each e^{send} , there is a corresponding message receive event on the destination node if the message is successfully delivered.

The happens-before relation \prec on events in an execution obeys the following rules:

- $e_1^{local} \prec e_2^{local}$ if both events happen on the same node and e_1^{local} happens before e_2^{local} in the local sequential event order.
- $e^{send} \prec e^{recv}$ if e^{send} and e^{recv} are the corresponding message send and receive pair.

2.2 Logical Clocks

Logical clocks can be used to determine the happens-before relation defined in §2.1. One instance of logical clocks is the Lamport clock [16]. Using Lamport clock, each node n_i in the system maintains a local clock c_i , represented as a natural number. The rules to update the clocks are:

- Upon a local event e_i^{local} , n_i increments its local clock.
- When n_i sends a message, n_i increments its local clock, and attaches the local clock value in the message.
- When n_i receives a message with a clock value c_m , it sets its local clock to $\max(c_i, c_m) + 1$.

The logical time of an event e , represented as c_e , is the local clock value after the clock update. Lamport clock guarantees the following property: If $e_1 \prec e_2$, then $c_{e_1} < c_{e_2}$. However, the inverse is not true, i.e., $c_{e_1} < c_{e_2}$ does not imply that $e_1 \prec e_2$. To be more precise, if $c_{e_1} < c_{e_2}$, either $e_1 \prec e_2$ or $e_1 \parallel e_2$, but not $e_2 \prec e_1$. For use cases that require accurate causality inference, Lamport clock falls short.

Vector clock addresses this shortcoming of Lamport clock. As the name suggested, a vector clock, v , consists of a vector of natural numbers. Cardinality of a vector clock equals the size of the system. Each node is assigned a unique index in the vector clock. We use $v[i]$ to denote the i th number in a vector clock v . The rules to update the vector clocks are:

- Upon a local event e_i^{local} , n_i increments $v_i[i]$.
- When n_i sends a message, n_i increments $v_i[i]$, and attaches v_i in the message.
- When n_i receives a message with a clock v_m , it sets v_i to v'_i , where $\forall p \in [0..S], v'_i[p] = \max(v_i[p], v_m[p])$, S is the size of the system. n_i then increments $v_i[i]$.

$v_i < v_j$ if and only if $\forall p \in [0..S], v_i[p] \leq v_j[p]$ and $\exists p \in [0..S], v_i[p] < v_j[p]$. By definition, there exists v_i and v_j such that neither $v_i < v_j$ nor $v_j < v_i$, i.e., \prec is a partial order on the set of vector clocks. Vector clock guarantees the following stronger property: $e_1 \prec e_2$ if and only if $v_{e_1} < v_{e_2}$.

2.3 Verifiable Computation

In systems where identities cannot be trusted (our target deployment model), publicly verifiable proofs are required to verify the claims made by the participants. More concretely, if a node claims that the output of applying a certain function μ on input x is y , the naive way to verify such a statement would be to re-execute the operation and compare the outputs. Such an approach might not be viable when the verifier does not have enough computational resources to execute the

function. For instance, the current bitcoin blockchain is approximately 450 GB in size. If a user wants to verify the latest block, he can either:

- (1) Trust the person who provided the latest block to him (this is extremely unwise).
- (2) Verify the whole chain himself from the genesis block; This takes a lot of compute time, storage space, and network bandwidth.

An argument system is a cryptographic construct to achieve verifiable computation without trusting the entity performing the computation. The goals of an argument system are quite simple. For a given statement $\mu(x) \xrightarrow{?} y$, it produces an accompanying proof π . This proof can be verified publicly to assert that the statement is true with all but a negligible probability. More concretely, a prover P wishes to convince a verifier V that it knows some witness statement w such that, for some public statement x and arithmetic circuit C , $C(x, w) \rightarrow y$.

Properties of an argument system. There are two properties an argument system must satisfy:

- (1) **Completeness:** A valid proof will always be accepted by a valid verifier.
- (2) **(Knowledge) Soundness:** If a prover attempts to generate a proof without a valid witness, this proof will only be accepted by the verifier with a negligible probability.

There are many types of argument system. One of the most commonly used argument systems is Succinct Non-interactive Arguments of Knowledge (SNARK). As the name suggested, using a SNARK, the verifier requires no further interaction with the prover, other than receiving the proof, when verifying; the proof itself is also short, while the time to verify is fast (at most logarithmic to the circuit size). If the witness w cannot be derived by the verifier with sufficient probability, then the SNARK is also considered *zero-knowledge* (zk-SNARK). CHRONO does not require the zero-knowledge property, so we omit the details of zk-SNARKs.

Recursive proof systems. SNARKs are useful in many settings, e.g., cloud computing, as it allows a verifier to validate computationally expensive function executions in a fraction of the time to run it. However, in some distributed computing scenarios, simply verifying a single execution is not sufficient. Instead, we wish to verify a particular non-deterministic chain of executions. Naively applying any off-the-shelf general circuit SNARK for every step will result in proofs and verification times that grows linearly. In a highly evolving and volatile system, these metrics are unacceptable.

There has been some recent development in verifiable computation that has the potential to address the above challenges. One particularly promising technique is recursive proof system. In a recursive proof system, the prover recursively proves the correct execution of incremental computations. Such technique can be applied to realize incrementally verifiable computation (IVC). In IVC, in each step of the computation, the prover takes the output and proof of the previous step, and produces an output and proof for the next step. A verifier only needs to verify the proof of a single step to ensure correct execution of the entire computation from genesis. Critically, both prover and verifier time are independent of the length of the computation. There exists quite a few constructions for recursive proofs in the wild, ranging from constructs like Halo[4] to PCD[8]. We envision more and more efficient constructs will be developed eventually.

3 CHRONO

We first define the high-level model and properties of CHRONO. The system consists of a set of nodes (n_1, n_2, \dots). Nodes can create, destroy, and mutate *objects*. They can also send objects to other nodes in the system. Besides send and recv, we define generic create and mutate functions:

- $create() \rightarrow o$: the create function generates an object.

- $\text{mutate}(o_1, o_2, \dots) \rightarrow o'$: the `mutate` function takes a list of objects o_1, o_2, \dots and generates a new object o' .

Unlike prior work [16], CHRONO concerns the causality of objects, not causality of events. We similarly define a binary relation \prec on the set of objects in an execution of a distributed system. \prec denotes the causal relationship between any two objects, *i.e.*, $o_1 \prec o_2$ if and only if o_2 is causally dependent on o_1 . Object causality in CHRONO is defined as follows:

- If an object o is generated from `create`, o is not causally dependent on any other object in the system, *i.e.*, $\forall o' \in O, o' \not\prec o$, where O is all objects ever generated in the execution.
- If an object o is generated from $\text{mutate}(o_1, o_2, \dots)$, o is causally dependent on o_1, o_2, \dots , *i.e.*, $o_1 \prec o, o_2 \prec o, \dots$

We note that the causality definition in CHRONO is stronger than those in prior work [16]. Instead of “possible influence”, \prec implies definite causal relationship between two objects¹. More formally, if $o_i \prec o_j$, there exist a sequence of `mutate` invocations such that $\text{mutate}(o_i, \dots) \rightarrow o_1, \text{mutate}(o_1, \dots) \rightarrow o_2, \dots, \text{mutate}(o_n, \dots) \rightarrow o_j$.

CHRONO provides the following *causality inference* guarantee:

THEOREM 3.1. *For any two objects o_i and o_j which are generated in an execution of a distributed system, CHRONO can deduce the causality relationship between the two objects, *i.e.*, CHRONO can correctly output $o_i \prec o_j, o_j \prec o_i$, or $o_i \parallel o_j$.*

4 DESIGN AND IMPLEMENTATION

This section details the concrete design of CHRONO using a novel logical clock construct coupled with verifiable computation.

4.1 System Setting

Suppose each object is defined as a tuple $o_i = (s_i, C_i)$, where $s_i \in \mathcal{S}$ is a state permutation in the set of all possible states \mathcal{S} . C_i is a logical clock construct. This indicates that for two objects $o_1 = (s_1, c_x), o_2 = (s_1, c_y)$ with homogeneous states, they are still considered unique $o_1 \neq o_2$ if the clock values are distinct.

CHRONO attributes two objects with the exact same state and clock values as identical. This, however, is not necessarily true. This is inevitable and might lead to certain false positives in causality evaluations.

There exists a dynamic set of objects O , which initially only includes the genesis object $o_0 = (s_0, C_0, d)$, where s_0 is the genesis state. There also exists a family of `mutate` functions $M = \{\mu_1, \dots\}$. For a new object o_i to be created, a `mutate` function must be operated on an existing object:

$$\exists o_{i-1} \in O, \exists \mu \in M : \mu(o_{i-1}) \rightarrow o_i, o_i \in O$$

Therefore, d for an object denotes the depth, or number of `mutate` functions applied onto o_0 to derive the object.

4.2 Logical clock Constructs

In this section, we will explore a few existing clock constructs and evaluate its feasibility of use in CHRONO.

¹We assume `mutate` implies definite causality. That is, if $\text{mutate}(o_1, o_2, \dots) \rightarrow o$, then o is causally dependent on o_1, o_2, \dots

4.2.1 Vector clocks. Vector clocks [28] have long been the standard to determine causality in systems. However, as briefly mentioned in §3, vector clocks do not necessarily draw accurate object causalities. Instead, vector clocks simply provide a temporal order and use that to infer possible causality; This will lead to great degrees of false positives.

We illustrate this with a simple example; Suppose we have two nodes A and B :

- (1) A and B start with the vector clock $[0, 0]$
- (2) A creates a new state, tags it with the clock value $[1, 0]$ and sends it to B .
- (3) B receives this new state and updates its clock to $[1, 1]$.
- (4) Suppose B now creates a new state by applying `mutate` to the genesis state instead of A 's newly produced state. B 's new clock value will be $[1, 2]$.

The issue is that although B 's new state does not depend on A 's state, its clock implies such. This is because the vector clock only captures the temporal order of states/objects produced by the nodes, and therefore probable causality; Furthermore, we conjecture this probability to be impossible to be derived.

Instead, we have to provide a way for B to generate distinct clocks based on its decision (to either `mutate` the genesis object or A 's object). This requires the decoupling of identities and clocks. Instead, each object is now tied to a logical clock that is used to infer its plausible relationship with another object.

4.2.2 Counting bloom clocks. The Bloom clock (BC) [26] is a logical clock construct that can be used to probabilistically determine causality between objects. The BC is based on the counting Bloom filter [3], and can be defined as a vector of n integers $[c_1, \dots, c_n]$.

In the context of CHRONO, when operating on an existing object $\mu(s_i, C_i, d) \rightarrow (s_{i+1}, C_{i+1}, d + 1)$, the BC protocol uses a family of m cryptographically secure hash functions h_1, \dots, h_m that produces m indices $h_1(s_{i+1}), \dots, h_m(s_{i+1})$. Each index is then mapped and incremented on C_i to produce C_{i+1} .

When comparing two objects, $o_x = (s_x, C_x, d_x)$ and $o_y = (s_y, C_y, d_y)$, there are 3 possible scenarios:

- (1) $\forall c_{xi} \in C_x, c_{yi} \in C_y, \exists c_{xj} \in C_x, c_{yj} \in C_y : c_{xi} \geq c_{yi} \wedge c_{xj} > c_{yj} \wedge d_x > d_y \Rightarrow (s_x, C_x) > (s_y, C_y)$.
- (2) $\forall c_{yi} \in C_y, c_{xi} \in C_x : c_{yi} \geq c_{xi} \wedge d_y \geq d_x \Rightarrow (s_y, C_y) \geq (s_x, C_x)$
- (3) (s_y, C_y, d_y) and (s_x, C_x, d_x) are concurrent.

The BC might postulate parenthood when in fact the objects are concurrent. This is due to possible hash collisions into the limited vector of size n .

The fundamental benefit of BC 's is its inherent agnosticism towards identities in the system; It can potentially be utilized by an unbounded number of nodes. This makes it suitable to be utilized in highly decentralized and permissionless settings.

However, BC suffers from two main issues:

Issue 1: limited lifespan. Eventually, a BC will increment to a point in which comparisons between two objects will always lead to a false positive. That is to say the BC can only hold a limited amount of objects before its utility is diminished. Therefore, to maintain its utility, we have to limit the number of objects a BC can hold. A naive reset might work, however it is crude. Comparisons between resets are impossible. Additionally, some synchrony might be required to derive consensus on the state of the clock before resets.

A simple fix would be to have a BC be represented by k bloom filters (BF) of size n . These k bloom filters is a sliding window on the history of objects, where objects outside these k bloom filters are forgotten.

The intuition is that after k mutate s, there is little to be gained from comparing a descendant state that is so far removed from its ancestor. Following that philosophy, more priority should be put into recent states (relative to the current state), and less priority to distant states. Especially in the BC protocol, a similar comparison will likely return a false positive.

Issue 2: multi-parent problem. In the BC protocol, all prior object clocks C_i are compressed into a single vector. However, this also means that similar objects (by means of indices after hashing) represented in the clock will potentially lead to false positives. The simple fix represented above resolves this to some extent. Since each BC is now represented by k bloom filters, we can analyze the state at each depth of mutation. This removes some false positives that previously existed in the original BC .

As illustrated with Figure 1, simply utilizing the bloom clock will lead to the false conclusion that o_3 is causally dependant on o_2 . This is due to the coincidental hash collisions. However, if a history of BF s are listed, it can be referenced and compared to eliminate o_2 as a false parent of o_3 .

$$\begin{array}{l}
 \text{o}_1 \text{ Bloom Clock} \\
 \boxed{BF_A} + \boxed{BF_B} + \boxed{BF_C} = \{0, 2, 1, 2, 1\} \\
 \\
 \text{o}_2 \text{ Bloom Clock} \\
 \boxed{BF_X} + \boxed{BF_X} + \boxed{BF_Y} = \{0, 3, 2, 1, 0\} \\
 \\
 \text{o}_3 \text{ Bloom Clock} \\
 \boxed{BF_A} + \boxed{BF_B} + \boxed{BF_C} + \boxed{BF_D} = \{0, 3, 2, 2, 1\}
 \end{array}$$

Fig. 1. How adding some history can be used to eliminate some false positives: Without the history, o_2 will be incorrectly determined as the ancestor to o_3 .

4.3 Decaying Onion Bloom Clocks

The naive resolution described in §4.2.2 would require an extremely inefficient $k * n$ bits.

In CHRONO, we introduce a novel logical clock construct: the Decaying Onion Bloom Clock (DOBC). DOBC an improvement over BC s:

- (1) DOBC probabilistically determines causality between objects with a depth difference of at most k .
- (2) DOBC addresses the issues described in §4.2.2, whilst utilizing less space. DOBC achieves this by keeping a finer grain memory of recent state transitions; This is opposed to distant state transitions, where its view is compressed to produce a coarser grained expression. To provide indefinite utility across any number of state transitions, DOBC eventually forgets states that are too distant. Eventually, states that are too distant are forgotten.
- (3) A sub-function that allows DOBCs of different depths to be *merged*. The causality utility is maintained with regard to any of its ancestors.

In this section we will describe the base DOBC protocol.

We generalize the Counting bloom filter construct to variable-sized Bloom filters (VBF_i), where each of its n indices are stored with exactly i bits. The DOBC also consists of $|L|$ layers, each layer l^i stores a pre-determined amount $|l^i|$ of VBF_j 's, where j^i is the size an index for each VBF at layer

l^i and $j^{i+1} > j^i$. For the sake of simplicity, let's assume $j^i \cong i$. Each VBF_i in a layer is ordered from $l_1^i, \dots, l_{|l^i|}^i$.

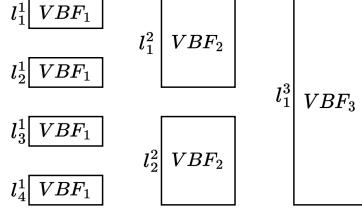


Fig. 2. An illustration of how a DOBC will look like with the setting: $j^i \cong i$, $|L| = 3$, $|l^1| = 4$, $|l^2| = 2$, $|l^3| = 1$

Suppose for a certain execution path, it produces an ordered set of objects $\{o_0, o_1, o_2, \dots\}$, where $\exists \mu \text{ in } M : \mu(o_i = (s_i, C_i, d)) \rightarrow (o_{i+1} = (s_{i+1}, C_{i+1}, d + 1))$. Initially, VBF_i s on all layers are set to 0. For illustration purposes, let's use the following settings:

$$|L| = 3, |l^1| = 4, |l^2| = 2, |l^3| = 1$$

This is illustrated with Figure 2.

When o_1 is generated, a Bloom filter BF_{s_1} is created by hashing s_1 with the family of m distinct hash functions and setting the corresponding indices to 1. It is important to note that $VBF_1 \cong BF$ if both contain the same number of indices.

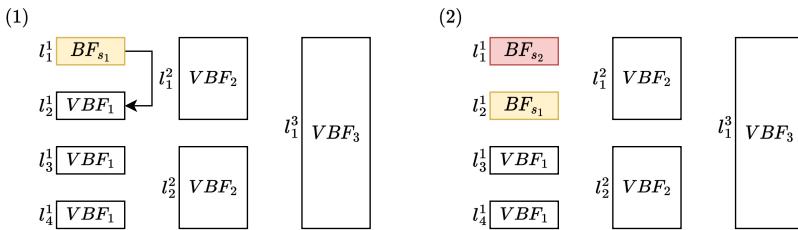


Fig. 3. (1) illustrates the DOBC for o_1 , (2) illustrates the DOBC for o_2 where BF_{s_1} is moved to l_2^1 to make space for BF_{s_2} .

BF_{s_1} is inserted into l_1^1 . When s_2 is reached, BF_{s_2} is created and placed into l_1^1 , and BF_{s_1} is moved to the next available slot (which in this case is l_2^1). DOBC for o_1 and o_2 is illustrated by Figure 3.

Eventually, as new objects (and states) are created, in the DOBC for a specific object (o_4), BF_{s_1} will be at $l_{|l^i|}^1 = l_4^1$. To make space for BF_{s_4} , BF_{s_1} instead moves to l_2^2 . In theory a VBF_2 can hold the compressed information of $2 * 2 - 1 = 3$ VBF_1 s. Therefore, $BF_{s_1}, BF_{s_2}, BF_{s_3}$ are added together before it moves to l_2^2 . This is illustrated by Figure 4. Intuitively, a VBF_{i+1} in layer l^{i+1} can store a multiple of VBF_i from the previous layer (l^i).

When $l_{|l^i|}^1$ has reached the maximum capacity, and a new state is reached, for the new object, $l_{|l^i|}^1$ is **deleted** and $l_{|l^i|-1}^1$ or $l_{|l^i|-1}^1$ takes its place. In the context of our example, $BF_{s_1}, \dots, BF_{s_6}$ is evicted from l_1^3 and $BF_{s_7}, \dots, BF_{s_9}$ takes its space. This is illustrated with Figure 5.

In our example, the DOBC keeps track of an average of $k = 13.5$ states, but it is clear to see that its ability to compare any causality drops every 4 objects.

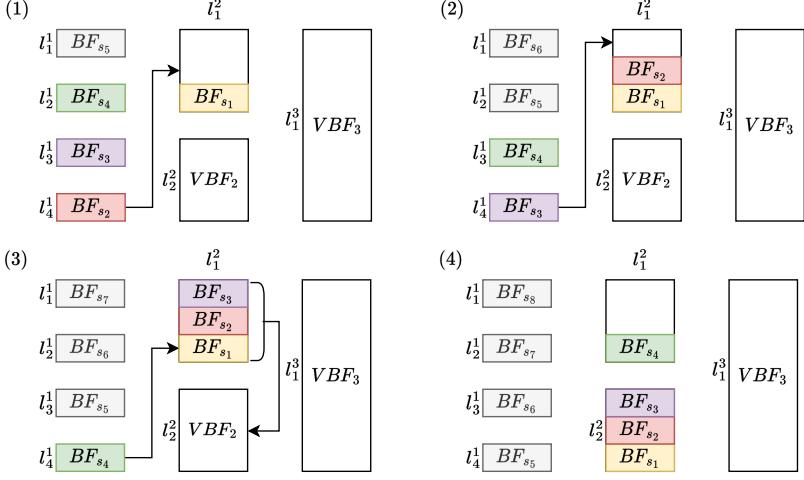


Fig. 4. (1) illustrates the DOBC for o_5 , (2) DOBC for o_6 , (3) DOBC for o_7 , (4) DOBC for o_8 .

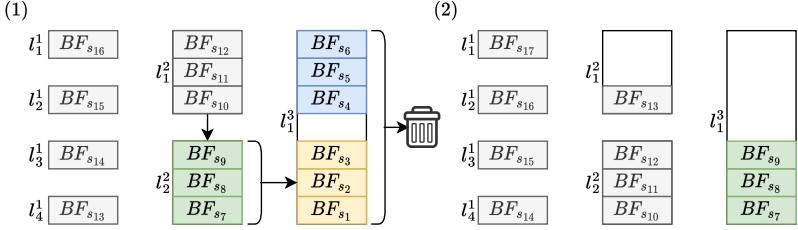


Fig. 5. (1) illustrates the DOBC for o_{16} . (2) illustrates the DOBC for o_{17} , where $BF_{s_1}, \dots, BF_{s_6}$ is evicted.

It is clear to see that there exists some wastage in utilization with the example DOBC, as a VBF_3 can in theory hold $2^3 - 1 = 7$ BF 's. However, because it can only hold a certain multiple of VBF 's from the previous layer, it only holds $(2^2 - 1) * 2$ BF s.

The maximum number of BF 's or unique states held by $l_{|l^i|}^{[L]}$ is therefore:

$$\gamma = \left(\prod_{i=1}^{i=|L|-1} \left\lfloor \frac{2^{j^{i+1}} - 1}{2^{j^i} - 1} \right\rfloor \right) * (2^{j^1} - 1)$$

The total number of states a DOBC can hold thus ranges from $[k, k - \gamma + 1]$ states, with an average of $k + \frac{\gamma+1}{2}$ states. Where for $|L| > 1$:

$$k = |l^1| * (2^{j^1} - 1) + \left(\sum_{i=2}^{i=|L|} \left\lfloor \frac{2^{j^i} - 1}{2^{j^{i-1}} - 1} \right\rfloor * |l^i| \right)$$

4.3.1 Comparing DOBCs. In this section, we will go through how two different DOBCs are compared to derive causality. In the naive approach mentioned in §4.2.2, it is quite obvious to see how clocks can be compared. However, in DOBC, we only keep a limited history k of states,

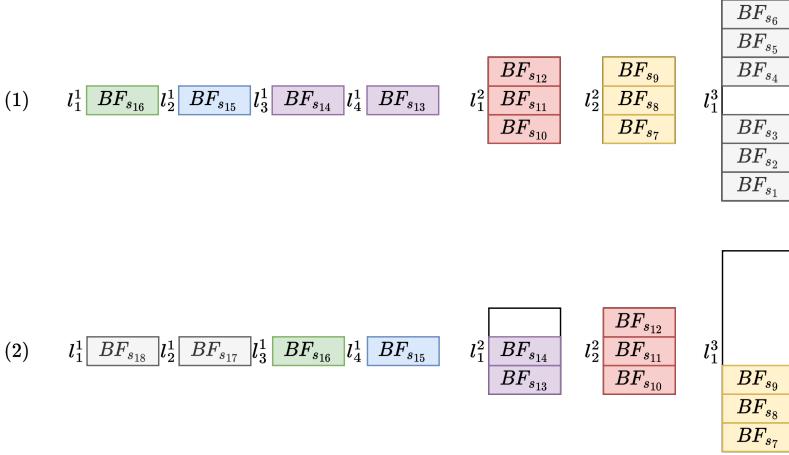


Fig. 6. (1) illustrates the DOBC for o_{16} . (2) illustrates the DOBC for o_{18} . To determine if o_{18} is causally dependent on o_{16} , we simply compare the similarly highlighted parts in both clocks. If the similarly highlighted parts in (2) is greater than or equal to the ones in (1) for all similarly highlighted parts, then we conclude $o_{18} > o_{16}$.

therefore only histories of a certain range can be compared. The greater the overlap, the lower the possibilities of false positives. We will utilize the same setting from §4.3 to illustrate an example. Suppose we have the DOBC for o_{18} and o_{16} , how we determine causality of o_{18} on o_{16} is illustrated with Figure 6: Since each state has differing depths, we compare different sections of its DOBCs to draw our causality conclusion. For example, $l_3^1 \in o_{18}$ should correspond to $l_1^1 \in o_{16}$. Similarly, the $l_1^2 \in o_{18}$ corresponds to addition of $l_3^1 \cap l_4^1 \in o_{16}$. Intuitively, two set of VBF's are comparable between two DOBCs if they correspond to the same depth. If all comparable VBFs in o_{18} are greater than or equal to the corresponding VBFs in o_{16} , then we draw the conclusion that $o_{18} > o_{16}$ with some acceptable probability.

4.3.2 Eliminating Wastage in DOBC. As briefly mentioned in §4.3, certain parameters will lead to bit wastage. This is not ideal if we wish to fully utilize every single bit in DOBC. We came up with two possible approaches to mitigate wastage. These approaches might require overhauls to the DOBC protocol:

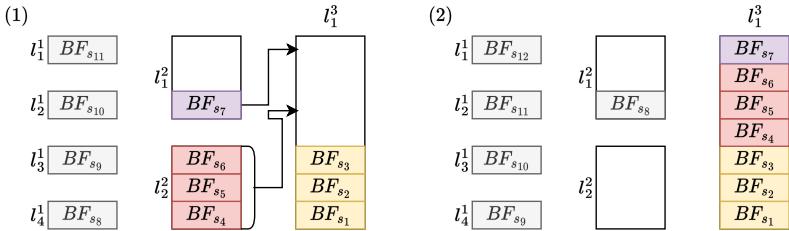


Fig. 7. (1) illustrates the DOBC for o_{11} . (2) illustrates the DOBC for o_{12} with incomplete decay; Although l_1^2 is not completely full, it is shifted along with l_2^2 to completely fill l_1^3 .

- (1) **Incomplete VBF decay:** We dictate that a $VBF_{j,i}$ does not necessarily have to be “full” before it is moved to the next layer. That is to say we change the “*a VBF_{i+1} in layer lⁱ⁺¹ can store a multiple of VBF_j from the previous layer (lⁱ)*” notion of the base DOBC protocol. We should be able to fully utilize all the space in all layers. This is illustrated by Figure 7. An important note is that $VBF_{j,1}$ must be of sufficient granularity to fill all the “gaps” of VBF’s of subsequent layers. Therefore, $j^1 = 1$ should always work.
- (2) **Perfect VBF decay:** If the next layer $VBF_{j,i}$ can exactly hold a multiple of $VBF_{j,i-1}$ s from the previous layer, then naturally, space will be fully utilized. More concretely, the number of BFs $VBF_{j,i}$ can hold is congruent to 0 modulo of the BFs $VBF_{j,i-1}$ can hold, given $|L| > 1$. An example would be to have the setting: $|L| = 3, j^1 = 1, j^2 = 2, j^3 = 4$. No space will be wasted since:

$$(2^2 - 1)\%1 = 0$$

$$(2^4 - 1)\%(2^2 - 1) = 0$$

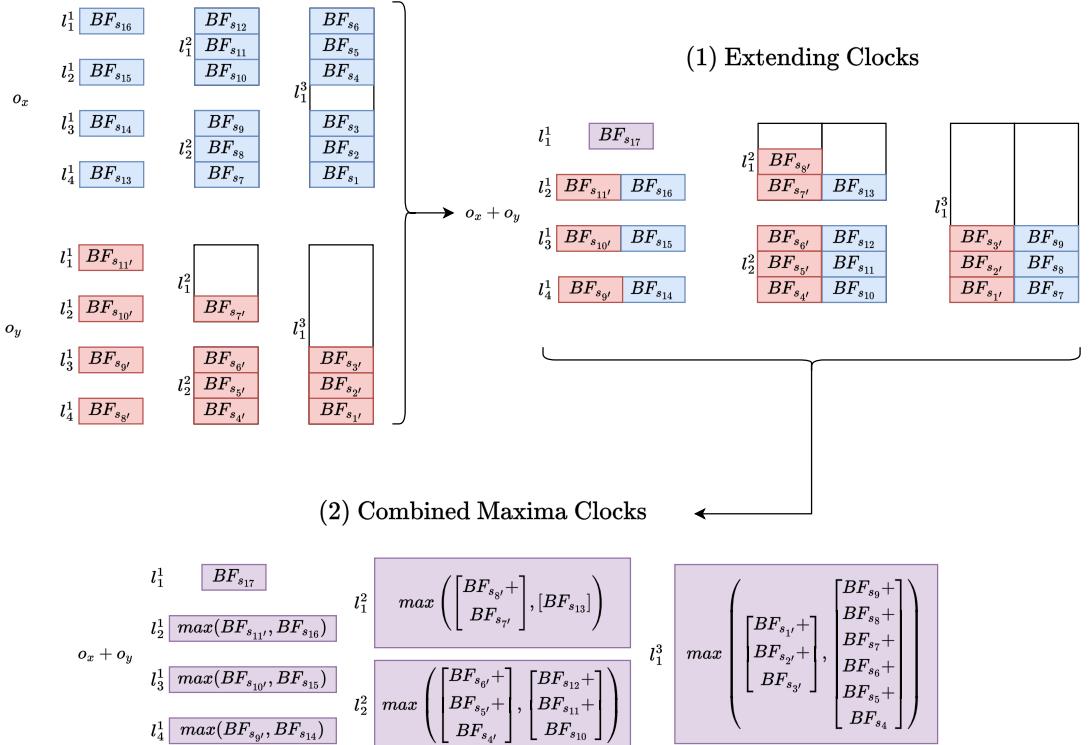


Fig. 8. Utilizing the same settings from §4.3: Suppose we wish to merge two objects o_x and o_y (1) The **Extending Clocks** solution will append the appropriate VBF’s to each other. (2)The **Combined Maxima Clocks** solution takes it a step further; trading false positives with space. The VBF’s at each position l_j^i are the maximum of the indices between the VBF’s seen in the extending clocks solution.

4.3.3 *Merging DOBCs.* Suppose if two objects were to be merged, the resultant state and its descendants will have some causal relation to both parents. In CHRONO, merging both DOBCs must

be done elegantly. This is to ensure that the causality of future descendants can still be adequately inferred.

DOBC has two methods to merge clocks, each at opposite ends of the spectrum when it comes to utility and its trade-offs.

Since DOBC only keeps track of at most k objects prior to the current one. When merging two objects $o_x = (s_x, C_x, d_x)$, $o_y = (s_y, C_y, d_y) : |d_x - d_y| > k$, the resultant object technically exists as both depth $d_y + 1$ and $d_x + 1$.

The unfortunate side effect of merging is that the new merged DOBC must keep track of both heights.

(1)

l_1^1	$BF_{s_{20}}$	l_1^2	$BF_{s_{11'}}$	$BF_{s_{12}}$
l_2^1	$BF_{s_{19}}$		$BF_{s_{10'}}$	$BF_{s_{11}}$
l_3^1	$BF_{s_{18}}$		$BF_{s_{9'}}$	$BF_{s_{10}}$
l_4^1	$BF_{s_{17}}$	l_2^2	$BF_{s_{8'}}$	BF_{s_9}
			$BF_{s_{7'}}$	BF_{s_8}
			$BF_{s_{13}}$	BF_{s_7}

(2)

l_1^1	$BF_{s_{21}}$	l_1^2	$BF_{s_{17}}$	$BF_{s_{12}}$
l_2^1	$BF_{s_{20}}$		$BF_{s_{11'}}$	$BF_{s_{11}}$
			$BF_{s_{10'}}$	$BF_{s_{10}}$
l_3^1	$BF_{s_{19}}$		$BF_{s_{9'}}$	BF_{s_9}
l_4^1	$BF_{s_{18}}$	l_2^2	$BF_{s_{8'}}$	BF_{s_8}
			$BF_{s_{7'}}$	BF_{s_7}

(3)

l_1^1	$BF_{s_{22}}$	l_1^2		$BF_{s_{15}}$
l_2^1	$BF_{s_{21}}$		$BF_{s_{18}}$	$BF_{s_{14}}$
l_3^1	$BF_{s_{20}}$		$BF_{s_{17}}$	$BF_{s_{13}}$
l_4^1	$BF_{s_{19}}$	l_2^2	$BF_{s_{11'}}$	$BF_{s_{12}}$
			$BF_{s_{10'}}$	$BF_{s_{11}}$
			$BF_{s_{16}}$	$BF_{s_{10}}$

Fig. 9. Since the Extending Clocks solution merges clocks at differing states of decay, decaying both clocks as is might lead to indefinite extra space utilization. To make the extra space utilization transient, we use the “more-decayed” clock as an anchor to decay the other “less-decayed” clock. As seen in (1), since the clock highlighted red is of a greater state of decay, therefore after (2), at (3) it also pre-emptively decays the blue clock. The result is a single VBF at l_1^2 .

Extending Clocks: The Extending clocks approach is the most naive approach. As the name suggests, and illustrated in (1) of Figure 8: The corresponding VBF’s after a merge is stored in a linked list configuration, where each $l_j^i : i = 1, j > 1$ is now a pair of VBF’s.

Comparing DOBCs to derive causality will now be done twice; once with the red highlighted VBF’s, another with the blue ones.

This merging solution will linearly grow the size of the resultant clocks per merge. However, this increase in space is transient and will only persist for at most k mutations. This is achieved by tweaking the decay function of DOBC, by making the new merged BF 's decay at different rates. This is illustrated in Figure 9.

Combined Maxima Clocks: Instead of naively appending clocks together in the previous solution, another alternative is to take the maxima of each index of the VBF 's. As illustrated in Figure 8, for l_1^2 , the VBF_2 will have its value at each index be the maximum of that of the corresponding two VBF 's from o_x and o_y .

Intuitively, such an approach will definitely increase the false positive rate. However, its inherent benefit is that the resultant merged DOBC will always remain the same size.

Furthermore, the false positive rate can be reduced by increasing n (number of indices) of the VBF s.

Hybrid Approach: A hybrid approach will be to employ the extending clocks method for a maximum of p merges. After which, older merges will be combined in the same approach outlined by the combined maxima clocks.

This will ensure a bound on the clock size, whilst having some good utility and lower false positive rates in some cases.

4.4 Verifiable Logical Clock Construction

To apply a proof system for CHRONO we first need to articulate the requirements we need, more precisely:

- (1) The proof system must support a known family of functions ($M = \{\mu_1, \dots, \mu_i, \dots, \mu_\omega\}$, $|M| = \omega$).
- (2) For a particular proof corresponding to a linear execution of n functions. The proof must assert to the validity that a non-deterministic multiset of functions of size n have been applied onto the genesis state. That is to say $\exists m = \{m_1, \dots, m_n\} : \forall m_i \in m, m_i \in M$ where there $\exists \pi$ that validates $s_n \leftarrow m_n(m_{n-1} \dots (m_1(s_0)))$, where s_0 is the genesis state.
- (3) Transparent setup: every one can join as is.
- (4) Proof size and verification time must remain constant.

At the time of writing, we will utilize the constructs introduced in Nova[15] and subsequently SuperNova[14].

4.4.1 R1CS (Rank 1 Constraint System). To understand Nova and by extension, SuperNova, we must first briefly explain R1CS. R1CS is a method to quickly verify that a particular binary or arithmetic execution has been carried out properly without actually running through the execution again. More precisely, R1CS allows the prover to generate a solution to some polynomial problem (represented by the arithmetic circuit), in which the verifier can verify in constant time.

The arithmetic circuit² can be viewed logically as a collection of gates, where each gate has a left and right input as well as a single output. How the gates are wired to produce the final outputs are defined by a set of 3 matrices $A, B, C \in \mathbb{F}^{q \times q}$. The prover also generates a solution vector $Z = W, x, 1, Z \in \mathbb{F}^q$, where W (or witness) are the intermediary outputs, x (or instance) are the inputs and outputs of the circuit, and 1 is a constant.

The verifier can simply verify the execution of the whole circuit as:

$$(A \cdot Z) \circ (B \cdot Z) = (C \cdot Z)$$

Where \cdot denotes matrix multiplication and \circ denotes the Hadamard product.

²We will omit details in regard to binary circuits as any binary circuit can be converted into an arithmetic circuit.

4.4.2 What is Nova? Nova, is an Incrementally Verifiable Computation (IVC) algorithm that requires no trusted setup, generates constant sized proofs for any step, and guarantees constant verification time. Nova introduced a novel method to combine two R1CS instances into a single instance. Naively adding two R1CS instances would lead to an incorrect instance. Therefore, Nova introduces a variant of R1CS: *Relaxed R1CS* which introduces an error vector $E \in \mathbb{F}^q$, where an instance (E, u, x) is satisfied if:

$$(A \cdot Z) \circ (B \cdot Z) = u \cdot (C \cdot Z) + E$$

Where $Z = (W, x, u)$. In particular, suppose there are two separate instances $Z_1 = (W_1, x_1, u_1)$ and $Z_2 = (W_2, x_2, u_2)$. $u \leftarrow u_1 + r \cdot u_2$ and E is a function of (Z_1, Z_2, r) . The resulting instance or *folded* instance can be simply verified by the verifier. The intuition is that if any of the relaxed R1CS instances that were folded is invalid, then the final folded relaxed R1CS instance will be invalid as well. Therefore, verifying the final folded relaxed R1CS instance asserts that arithmetic circuit has been executed correctly a particular number of times.

Verifier work is further reduced by the introduction of the *committed relaxed R1CS* scheme. This scheme allows the prover to utilize additively-homomorphic commitment schemes (like Pedersen commitments) to save the verifier from generating E themselves. Instead, the prover will send commitments for E_1, E_2, W_1, W_2 as well as another matrix T which is a result of a function of Z_1, Z_2 .

The verifier can additively combine the commitments to generate the committed folded instance. The prover will then reveal the actual folded instance. If it matches, the verifier can simply take the folded instance as is to use for verification.

The resultant proof structure for the i^{th} step is a folded committed relaxed R1CS instance and witness pair asserting to the validity of executions up till step $i - 1$, and a single relaxed R1CS asserting to the validity of step i .

The scheme is then made *non-interactive* by utilizing a public coin³ hinging on the Fiat-Shamir heuristic.

4.4.3 Nova for a family of functions. Traditional IVCs like Nova typically are designed for a single function. To allow Nova to satisfy requirement (2) above, we can utilize a universal circuit. Intuitively, a universal circuit can be visualized as a circuit made by combining n sub-circuits, each representing the execution to a particular function. The inputs of this universal circuit will then “select” a particular sub-circuit to execute.

The major downside to utilizing general circuits is that for any step of the execution, the whole circuit is actually still processing some input and generating some output. This means the prover will be doing some unnecessary work. Additionally prove sizes might be larger.

SuperNova[14] was developed to circumvent this issue, we will elaborate this in the following text.

4.4.4 SuperNova: Universal machines without universal circuits. SuperNova generalizes Nova’s IVC to *non-uniform* IVC, i.e., there exists a family of functions $F = \{f_1, \dots, f_n\}$, and a control function φ which determines the function to run at a particular step j . That is to say at the j^{th} step, the prover proves that $f_j, j = \varphi(W_i, x_i)$ has been correctly applied with witness instance pair (W_i, x_i) to produce x_{i+1} .

Recursive Proofs in SuperNova: It is not possible to naively apply the folding scheme developed in Nova, because each function (and the corresponding circuit) is structurally heterogeneous.

³This can be instantiated by using a cryptographic-secure hash function

A SuperNova proof therefore maintains a list of running instances U_i , where $U_i[j]$ is the folded instance of all previous invocations of f_j before the i^{th} step. It also contains a corresponding list of Witnesses W_i , as well as an instance witness pair (u_i, w_i) that asserts to valid execution of step i .

Furthermore, instead of simply applying the functions within the function family as is, SuperNova instead runs the *augmented* version of the function $f'_{\varphi(W_i, x_i)}$.

In essence, the augmented function does not just simply run $f_{\varphi(W_i, x_i)}(W_i, x_i)$ to output x_{i+1} . It also checks that $U_i, \varphi(W_{i-1}, x_{i-1})$ are indeed produced by the prior step if it is contained in u_i . This asserts that checking U_{i+1} is the same as checking (U_i, u_i) . The augmented function then folds u_i into $U_i[\varphi(W_{i-1}, x_{i-1})]$, and produces $\varphi(W_i, x_i)$.

$$((i+1, x_0, x_{i+1}), U_{i+1}, \varphi(W_i, x_i)) \leftarrow f'_{\varphi(W_i, x_i)}(U_i, u_i, \varphi(W_{i-1}, x_{i-1}), (i, x_0, x_i, W_i))$$

Resulting in the witness pair (u_{i+1}, w_{i+1}) .

Intuitively, verifying U_{i+1} is equivalent to verifying the prior i steps. u_{i+1} asserts the $i+1$ step. Therefore, the proof for step i can be expressed as:

$$\Pi_i = ((U_i, W_i), (u_i, w_i))$$

Additional details on SuperNova proofs using committed relaxed R1CS instances can be found in the original paper.

We aim to utilize the Non-Uniform Incrementally Verifiable Computation scheme described above for CHRONO. As such, each function in F corresponds injectively to a specific mutate function in M . The depth value d simply corresponds to i in each instance u_i . The object state and clock value corresponds to x_i .

5 USE CASES

So far, we have discussed the high-level properties of CHRONO, and a concrete design of CHRONO using DOBC and verifiable computation. In this section, we describe a few use cases of CHRONO.

5.1 Weakly Consistent Data Store

Prior systems [10] have built data stores with eventual consistency using logical clocks. Similarly, we leverage CHRONO to build a weakly consistent decentralized data storage, KSTORE. KSTORE implements a key-value storage interface. Each unique *key* is mapped to an arbitrarily-sized value. KSTORE is fully decentralized and permissionless. Any node can join and leave the system at any time. Compared to its strongly consistent counterparts [6, 22], KSTORE offers higher efficiency, scalability, and availability.

KSTORE provides *eventual consistency*: if no further writes are applied to a key, eventually all nodes observe the same value mapped to the key. Each KSTORE node maintains a subset of the keys in the key-space. We use a distributed hash table (DHT) [13, 21, 29] with virtual nodes for key-space partitioning and request routing. For fault tolerance, each key is stored on R virtual nodes closest to the key hash on the hash ring, where R is a configurable parameter. This set of virtual nodes is called the *replica group* for the key. Higher R offers stronger fault tolerance, but results in longer update latency and higher storage overhead.

KSTORE's storage API exposes three external operations, Get, Insert, and Update. Get takes a key and returns the value mapped to the key. Update maps a new value to an existing key. Insert creates a new key into KSTORE with an initial mapped value. Insert also takes an optional user-defined Merge function. The Merge function takes a set of values as input and outputs a single value. For instance, a Merge function for numerical value types could be maximum, and union for set value types.

When a client invokes `Insert`, the request is routed to one of the R responsible virtual nodes on the DHT. The client can choose any reachable nodes, L , in the replica group. Upon receiving the `Insert` request, L invokes `create` to generate an object, with the genesis state set to the value in the request. The object state also includes the `Merge` function in the request. L then forwards the generated object to the remaining nodes in the replica group. Each node in the group verifies the validity of the object using the attached proof (§4.4) and stores it locally.

When a client invokes `Update` on a key, the request is similarly routed to one of the R responsible virtual nodes, L . Note that L does not need to be the same node that creates the object. L then invokes `mutate` with the locally stored object o_l as input, *i.e.*, $\text{mutate}(o_l) \rightarrow o'_l$. The output object state is set to the value in the `Update` request. L then forwards o'_l to the other nodes in the replica group. When a replica node receives o'_l , it uses CHRONO to determine the causality relation between o'_l and its locally stored object o . If $o'_l < o$, the node ignores the object. If $o < o'_l$, the node replaces the local object with o'_l . Otherwise, $o \parallel o'_l$ and the node invokes $\text{mutate}(o'_l, o) \rightarrow o'$, and stores the new object o' . When invoking `mutate`, the node applies the `Merge` function stored in the object.

When a client invokes `Get`, it simply routes the request to any of the R nodes in the replica group. The node returns the object if it is stored locally. The client iterates through the replica group until the object is found.

5.2 Anti-Censorship Decentralized Social Network

The second use case is a decentralized social network, KSOCIAL, which we built atop CHRONO. In KSOCIAL, users (represented by a private/public key pair) publish posts (*e.g.*, short text, blogs, and photos) to the network, and subscribe to other users to receive their posted content. Users can also react and comment on posted content, both of which are fetched alongside the content.

KSOCIAL stores the status and all published content of a user in a CHRONO object with the type `UOBJ`.⁴ All posts are signed by the publishing user. KSOCIAL defines a `Update` and a `Merge` function. `Update` takes a `UOBJ` and produces a new `UOBJ` with the newly published posts added to it. `Merge` takes multiple `UOBJS` for the same user and merge their content to produce a new `UOBJ`. To read the posts of a user, a subscribed client simply fetches the corresponding `UOBJ`. We omit the exact format of `UOBJ` and detailed implementation of `Update` and `Merge`.

KSOCIAL uses a DHT [13, 21, 29] for content routing. Each user `UOBJ` is mapped to R nodes closest to its public key hash on the hash ring, with R a configurable parameter. Similar to the data store, these R nodes are called the replica group of the `UOBJ`. To publish a post, the user first fetches its own `UOBJ` from any of nodes in the replica group. It can optionally cache the `UOBJ` to avoid subsequent fetches. If the `UOBJ` is not available, the user creates a new `UOBJ` by calling `create()`. The user then applies `mutate()` on the `UOBJ` with the `Update` function to add the post, and sends the resulting `UOBJ` to all nodes in the replica group. When a node receives a `UOBJ`, it verifies the validity of the object (*e.g.*, `UOBJ` contains the correct signatures from the user) and the clock, and applies `mutate(uobj, uobj')` with the `Merge()` function, where `UOBJ'` is the currently stored user object.

To subscribe to another user, the client sends a `Subscribe` message to all R nodes in the replica group of the target user. The replicas records this subscription. Once a replica node receives a `UOBJ` generated by the target user, it sends a notification to the subscribed client, who then fetches `UOBJ` from the replica. The client verifies the validity of the object before accepting it. Due to asynchrony and network partitions, it may receive stale or diverged `UOBJS`. To address this issue,

⁴For simplicity, we store both the metadata and the content in the CHRONO object. An optimized implementation can store content separately, and only saves content hashes, which can be used as pointers, in the CHRONO object.

the client stores a uobj for each subscribed user. When it received a uobj' from a replica, it applies `mutate(uobj, uobj')` with the Merge function to update the object.

6 CONCLUSION

In this work, we design a new logical clock system, CHRONO. CHRONO addresses key limitations of prior logical clock constructs. It scales perfectly in a decentralized network with dynamic membership, and tolerates Byzantine behaviors regardless of the proportion of adversaries. CHRONO achieves the above strong properties by introducing a novel logical clock structure, the Decaying Onion Bloom Clock (DOBC). It additionally applies non-uniform IVC to ensure independently verifiable construction of DOBC even in the presence of Byzantine behaviors. To showcase the capability of verifiable causality enabled by CHRONO, we have built a weakly consistent key-value store and an anti-censorship social network using CHRONO.

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