Performance-Optimal Read-Only Transactions (Extended Version)

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Abstract

Read-only transactions are critical for consistently reading data spread across a distributed storage system but have worse performance than simple, non-transactional reads. We identify three properties of simple reads that are necessary for read-only transactions to be performance-optimal, i.e., come as close as possible to simple reads. We demonstrate a fundamental tradeoff in the design of read-only transactions by proving that performance optimality is impossible to achieve with strict serializability, the strongest consistency.

Guided by this result, we present PORT, a performance-optimal design with the strongest consistency to date. Central to PORT are version clocks, a specialized logical clock that concisely captures the necessary ordering constraints. We show the generality of PORT with two applications. Scylla-PORT provides process-ordered serializability with simple writes and shows performance comparable to its non-transactional base system. Eiger-PORT provides causal consistency with write transactions and significantly improves the performance of its transactional base system.

1 Introduction

Large-scale web services are built on distributed storage systems. Sharding data across machines enables distributed storage systems to scale capacity and throughput. Sharding, however, complicates building correct applications because read requests sent to different shards may arrive at different times and thus return an inconsistent view of the data.

Consistently interacting with data in a distributed storage system thus requires transactional *isolation*, which unifies the view of data across shards. While general transactions provide isolation for reading and writing across shards, this paper focuses on *read-only transactions* that only read data. Read-only transactions are prevalent: they are used in systems without general transactions [5, 15, 36, 37, 39] and, even for systems with general transactions, they are often implemented with a specialized algorithm [11, 12, 39, 43, 44, 45, 57]. Read-only transactions are practically important because reads dominate real-world workloads: Facebook reported 99.8% reads for TAO [9] and Google reported three orders of magnitude more reads than general transactions for the ads workload (F1) that runs on Spanner [11]. They are also theoretically important because they provide a lower bound for other classes of transactions: anything impossible for read-only transactions is also impossible for any class of transactions that includes reads.

The dominance of reads in real-world workloads makes their performance the primary determinant of end-user latency and overall system throughput. Unfortunately, read-only transactions perform worse than simple, non-transactional reads due to the coordination required to present a consistent view across shards. Whether a view is consistent is determined by a system's *consistency model*: stronger consistency provides an abstraction closer to a single-threaded environment, greatly simplifying application code [38]. Thus, ideal read-only transactions would provide the strongest consistency *and* have optimal performance.

What is the "optimal" performance? Although recent work has studied optimality through the lens of latency [39], it did not consider throughput, which adds a fundamentally new dimension to this question. In this paper, we formalize the notion of optimality for read-only transactions and use it to explore the tradeoff between their consistency and performance. We posit that optimality should be defined by the algorithmic properties of simple reads that comprise a read-only transaction. *Simple reads* do not provide transactional isolation and thus capture the minimum work required to read data in a distributed storage system: **O**ne round of **N**on-blocking communication with a **C**onstant amount of metadata. As we elaborate in §3, these algorithmic properties (N, O, and C) precisely capture the additional coordination incurred by read-only transactions to present a consistent view. Thus, we define *performance-optimal* read-only transactions to be those with the same NOC properties as simple reads.

Our main theoretical result is that performance optimality is impossible in a system that provides **S**trict serializability—the strongest type of consistency. Specifically, our NOCS Theorem states that no read-only transaction algorithm can be performance optimal and provide strict serializability. This result holds even in systems that only support non-transactional writes, and thus applies to systems with and without more general types of transactions. It shows there is a fundamental choice in the design of distributed storage systems: they can either provide the strongest consistency or

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the best performance for read-only transactions, not both.

Guided by our impossibility result, we present the PORT design, which enables performance-optimal read-only transactions with the strongest consistency to date: process-ordered serializability. Previous performance-optimal transactions only provided relatively weak consistency (§5.1). PORT provides performance-optimal read-only transactions without harming either the latency or throughput of writes. The main mechanism enabling our design is a new specialized logical clock, called *version clocks*, that concisely capture the ordering constraints imposed by process-ordered serializability on read and write operations. PORT uses version clocks to tightly co-design its components. Version clock values index its multi-versioning framework, control what read-only transactions see, and control where writes are applied. They also enable optimizations that avoid the work of applying some concurrent writes (*write omission*) and limit the staleness of reads (*data freshness*).

We use the PORT design with the write omission and data freshness optimizations to build a new storage system, Scylla-PORT, that adds performance-optimal read-only transactions to ScyllaDB [53] while providing process-ordered serializability. As a single-versioned, non-transactional system, ScyllaDB provides a clean slate for implementing PORT and allows us to quantify the overhead of our performance-optimal read-only transactions relative to simple reads. ScyllaDB's simple reads are a challenging baseline as the system is aggressively engineered for high performance, including core-level sharding and custom lock-free data structures. Our evaluation shows that PORT's read-only transactions introduce low overhead, achieving throughput and latency within 3% of ScyllaDB on most of the workloads we test, and within 8% in the worst case. Our evaluation also compares PORT to a variant of OCC that is optimized for read-only transactions. PORT significantly outperforms OCC with at least double the throughput and at most half the latency because Scylla-PORT always finishes in one round while OCC's best case is two rounds.

We also applied PORT with data freshness optimizations to Eiger [37] to make its read-only transactions performance optimal while preserving the system's causal consistency and write transactions. Eiger is a challenging baseline because it can complete read-only transactions in a single round. Our evaluation shows that Eiger-PORT significantly improves performance with throughput up to 3× higher and latency up to 60% lower than Eiger. These improvements do come with some staleness relative to strongly consistent systems, but our data freshness optimizations keep the staleness low.

In summary, this work makes the following contributions:

- A fundamental understanding of the tradeoff between performance and consistency for read-only transactions. This includes a precise definition of performance optimality (§3) and the NOCS Theorem that proves optimality is impossible with strict serializability (§4).
- The PORT design that achieves performance-optimal read-only transactions with the strongest consistency to date by leveraging version clocks, a new type of logical clock that concisely captures the necessary ordering constraints (§6).
- The implementation and evaluation of two new systems based on the PORT design. Scylla-PORT is a clean-slate application of PORT to a non-transactional system, ScyllaDB (§7). Eiger-PORT makes the read-only transaction algorithm of Eiger performance optimal (§8, §9).

2 Background

Web service architecture. Web services are typically built using two tiers of machines: a stateless frontend tier and a stateful storage tier. The frontends handle end user requests by executing application logic that generates sub-requests to read or write data in the storage tier. We refer to the frontends as *clients* and the storage machines as *servers*, as is common. Web services are often replicated across multiple datacenters. For simplicity, we focus on a single datacenter setting, but our results also apply to multi-datacenter settings.

Read-only transactions. Read-only transactions provide a consistent, unified view of data spread across servers in a storage tier. They consist of one or more logical rounds of simple read requests issued in parallel to the servers, which collectively return a view satisfying the consistency model of the system. *One-shot transactions* [27] know the data locations of all reads prior to the transaction start. In contrast, *multi-shot transactions* may include key dependencies, where the data read in one shot determines what data to read in later shots. We study one-shot transactions for simplicity, because they are common, and because what is impossible for them is also necessarily impossible for multi-shot transactions. The NOCS Theorem thus also applies to multi-shot transactions. The PORT design for read-only transactions can be easily extended to support multi-shot transactions.

3 Performance-Optimal Read Transactions

This section explains the challenges of reasoning about performance, the rationale of our approach, and the set of algorithmic properties that define optimal performance.

3.1 Reasoning About Performance

The key challenges to reasoning about performance are identifying the fundamental overhead of read-only transactions and modeling it in a way that connects with practical designs.

Capturing the fundamental overhead. As a layer built upon simple reads, the performance of a read-only transaction is impacted by both the engineering factors in executing simple reads and the algorithmic properties of coordinating simple reads to find a consistent view. Engineering factors, such as load balancing, batching, and networking, equally affect simple reads and the read-only transactions built on them. In contrast, the algorithmic properties, such as rounds of communication, only affect read-only transactions. For

instance, a read-only transaction protocol that requires multiple round trips incurs overhead due to those extra rounds of messages, while the read requests in each round are engineered the same as simple reads.

Thus, this work focuses on the algorithmic properties that capture the fundamental overhead of read-only transactions. These properties capture the additional overhead to coordinate a consistent view and are orthogonal to underlying engineering factors. More specifically, we answer the question, "given a system, how low can we make the performance overhead of read-only transactions relative to the system's simple reads?"

Being useful in practice. Our goal is to model optimal performance in a way that is both *theoretically insightful* and *practically useful*. Theoretical insights help clarify fundamental tradeoffs between performance and guarantees. Practically useful guidance helps us design better systems. Our NOCS Theorem (§4.1) and properties yield theoretical insights that lead to a better design, PORT (§6), that achieves better performance in practice. This shows that our modeling is practically useful (§5).

3.2 Approach Overview

To reason about optimal performance in a practically useful way, we examine the mechanisms used in existing systems to coordinate a consistent view across shards. These coordination mechanisms include blocking, extra messages, and metadata. Some systems *block* read operations until a consistent view is ready—e.g., systems that use two-phase locking. Almost all systems use *extra messages* to determine a consistent view, such as multiple round trips on the critical path of reads—e.g., OCC [28]—or approaches that asynchronously coordinate a consistent view—e.g., COPS-SNOW [39], GentleRain [16], Cure [4]. Finally, all systems we are aware of use *metadata* to help compute a consistent view for read-only transactions to return—e.g., timestamps, transaction ids. Figure 11 in Section 10 shows representative systems that use these mechanisms.

These coordination mechanisms cause read-only transactions to have worse performance than simple reads, as they consume additional system resources. Therefore, we define performance-optimal read-only transactions to be those that require the least amount of each coordination mechanism, making their performance closest to that of simple reads.

3.3 NOC: Optimal Performance

We now explain the NOC properties, which we use to define optimal performance for read-only transactions.

N: Non-blocking. A read-only transaction algorithm is *non-blocking* if servers process each read request without waiting for any external event, such as a lock to become available, a message to arrive, or a timer to expire.

Blocking for a read request increases the latency of the read-only transaction: the more time spent blocking, the longer the transaction takes to complete. It also decreases throughput due to the overhead of context switches. In practice, blocking can incur more serious performance issues, e.g., CPU underutilization and deadlocks, which are increasingly pronounced in modern services [50, 58].

O: One-round communication. A read-only transaction algorithm has *one-round communication* if it uses exactly one parallel round of on-path messages and does not have any off-path messages. This matches the messages of simple reads: the client sends a single request to each server holding relevant data, and each server sends a single response back. It excludes algorithms that use extra messages, such as those that require multiple rounds of on-path communication, e.g., to abort/retry. It also disallows coordinating through *off-path messages*, i.e., messages that are necessary for the read-only transactions but lie off the critical path of reads.

A message is an off-path message for read-only transactions if its removal affects *only* the correctness of read-only transactions. For example, COPS-SNOW [39] adds extra messages to writes. These messages are used for read-only transactions to find a consistent snapshot and are not necessary for processing writes. Because only the correctness of read-only transactions is affected if these messages are removed, they are off-path messages.

Additional rounds of on-path messages increase the latency of read-only transactions. Both extra on-path and off-path messages decrease system throughput because transmitting and processing them consume network and CPU resources that could otherwise be used to service requests.

C: Constant metadata. Metadata is the information required by a read-only transaction algorithm to coordinate consistent values. It is information a server needs to find the specific version of the data that will produce a consistent cross-shard view across reads in the same transaction. Examples of metadata include timestamps [2, 11], transaction ids [39, 47], and identifiers of participating servers [6].

A read-only transaction algorithm has *constant metadata* if the amount of metadata required to process each of its read requests is constant, i.e., it does not increase with the size of the system, the size of the transaction, or the number of concurrent operations. An example of constant metadata is one timestamp per read request for snapshot reads in Spanner [11]. An example of non-constant metadata is COPS-SNOW [39], which requires information about *many* concurrent read-only transactions to process each read request.

Transmitting and/or processing extra metadata consumes more resources, increasing latency and decreasing throughput. Its negative impact on performance has been reported in recent work [14, 15, 16]. We use Big-O notation, i.e., "constant," to capture the algorithmic complexity of metadata required for coordination. In practice, system designers should aim for as low a constant as possible. We realize this in our PORT design, which uses a single integer per read request.

Performance optimality. We deem an algorithm *performance optimal* if it satisfies the N+O+C properties because they capture the least coordination overhead and thus enable performance as close as possible to simple reads.

4 The NOCS Theorem

An ideal system would have performance-optimal read-only transactions that provide the strongest consistency. Our NOCS Theorem proves this ideal is impossible.

S: Strict serializability. Strict serializability is the strongest form of consistency, equivalent to linearizability [26] with the addition of transactional isolation. It requires that there exists a legal total order of transactions that respects the real-time order between transactions [48]. A *legal total order* ensures that the results of transactions are equivalent to a single entity processing them one by one. The *real-time order* ensures that if transaction T_2 starts after transaction T_1 ends, then T_1 must appear before T_2 in the total order. If T_1 and T_2 have overlapping lifetimes, then they are concurrent and can be placed in either order. Strict serializability gives application programmers the powerful abstraction of programming in a single-threaded, transactionally isolated environment.

4.1 NOCS is Impossible

Our main result is that performance-optimal read-only transactions (N+O+C) cannot provide strict serializability (S). This section present a condensed version of the proof. The full proof appears in Appendix A.

The NOCS Theorem. *No read-only transaction algorithm satisfies all NOCS properties.*

System model. We model a distributed system as a set of processes that communicate by sending and receiving messages. This model is similar to that used in FLP [18]. A set of client processes (clients) issue requests to server processes (servers) that store the data. Processes are modeled as deterministic automata: in each atomic step, they may receive a message, perform deterministic local computation, and send one or more messages to other processes.

A transaction (operation) starts when a client sends the request messages to servers and ends when the client receives the last necessary server response. Two transactions (operations) are concurrent if their lifetimes overlap, i.e., neither begins after the other ends. If concurrent transactions (operations) access the same data item, then they conflict.

Assumptions. We make the following assumptions:

(A-0) There are ≥ 2 servers and ≥ 2 clients. Otherwise, optimal performance and strict serializability are trivial. All reads and writes eventually complete.

(A-1) The network and processors are reliable. Every message is eventually delivered and processed by the destination process. Processes are correct and never crash. By proving our impossibility result under these favorable conditions, it will necessarily hold when the system can fail.

(A-2) The network is either asynchronous [21], i.e., messages can be arbitrarily delayed, or partially synchronous [17], i.e., physical clocks ensure bounded delays.

Proof intuition. Due to network asynchrony, it is always possible for a read-only transaction to conflict with write operations and other concurrent read-only transactions. These requests occupy *an unstable region* in the system's history, where conflicts are possible and a total order has not yet been established. In contrast, the *stable region* is the part of history that precedes the unstable region, where all writes have committed and system states are finalized. Reading in the stable region is easy as there are no conflicting writes. However, we show that the real-time order requirement of S requires read-only transactions that are N+O to interact with the most recent writes in the unstable region (Lemma 1). Doing this while ensuring a legal total order requires transferring metadata between the servers (Lemma 2), either proactively through read requests or through the write protocol. By extending this construction, we show that processing a set of read-only transactions requires metadata that is asymptotically larger than the total size of the transactions, regardless of how the metadata is transferred (Lemma 3). This violates C, proving the theorem.

Proof. Suppose the system has two servers, S_1 and S_2, and multiple clients. Let `ALG` be any read-only transaction algorithm that satisfies N+O+S. Let $R = \{r_1, r_2\}$ be a read-only transaction that executes `ALG`, issued by client C_R. Let w_1 and w_2 be simple write requests issued by client $C_w \neq C_R$, where $w_1 \rightarrow w_2$ in real-time, i.e., w_2 is sent after the response for w_1 is received. We place no restrictions on the write protocol (beyond assumption A-0). Consider the execution e_1:

S_1 : r_1, w_1
S_2 : w_2, r_2

Suppose there is no metadata in the system, i.e., no information for coordinating consistent values between requests.

Lemma 1. *Without metadata, a read-only transaction that is N+O+S must observe any write that precedes it at a server.*

Proof Summary. Without metadata, S_2 cannot distinguish between an execution where w_2 and R are concurrent and one with $w_2 \rightarrow R$ in real-time. The latter requires $r_2 \in R$ to observe w_2 to satisfy S's real-time order. ■

Lemma 2. *Processing e_1 while satisfying N+O+S requires dependency $R \rightarrow w_1$ to be transferred from S_1 to S_2.*

Proof Summary. Lemma 1 states that, without metadata, r_2 must observe w_2, implying $w_2 \rightarrow R$. But r_1 must be processed before w_1 to satisfy N+O, implying $R \rightarrow w_1$. Since $w_1 \rightarrow w_2$ by construction, this creates a cycle, violating the legal total order of S. Using basic two-party communication complexity, we show that legalizing the total order requires transferring $R \rightarrow w_1$ from S_1 to S_2. ■

We now extend e_1 with more read-only transactions, servers, and write requests, and apply the structure above to

force more dependency metadata to transfer between servers. We then quantify this metadata and show that it violates C.

Proof of the NOCS Theorem. Suppose the system has M^2+1 servers $S_1, S_2, \ldots, S_{M^2+1}$. Let $R_1, R_2, \ldots, R_N$ be N read-only transactions that execute ALG, where each R_i sends a read request to S_1 and $M-1$ other servers, such that every server other than S_1 receives N/M read requests. (In practice $M^2 \ll N$, but our construction works for any $N, M \geq 1$.) The specific mapping of read requests to servers is unimportant; we lay them out sequentially by transaction index below. Let $r_{i,j}$ be a read request of R_i assigned to S_j. We assign one read request from each of R_1 to $R_{N/M}$ to S_2, one read request from each of $R_{N/M+1}$ to $R_{2N/M}$ to S_3, and so on, restarting at R_1 after reaching R_N. Let $w_1, w_2, \ldots, w_{M^2+1}$ be M^2+1 simple writes issued to each server by a distinct client C_w that does not issue any read-only transactions. Suppose w_1 precedes all other writes, i.e., $w_1 \rightarrow w_j$ for $j = 2, \ldots, M^2+1$, and all read-only transactions are concurrent with all writes. Consider the execution e_*:

$$
\begin{array}{lll}
S_1: & r_{1,1}, \ldots, r_{N,1}, w_1 & \\
S_2: & & w_2, r_{1,2}, \ldots, r_{N/M,2} \\
S_3: & & w_3, r_{N/M+1,3}, \ldots, r_{2N/M,3} \\
\vdots & & \\
S_{M+1}: & & w_{M+1}, r_{N-N/M+1,M+1}, \ldots, r_{N,M+1} \\
S_{M+2}: & & w_{M+2}, r_{1,M+2}, \ldots, r_{N/M,M+1} \\
\vdots & & \\
S_{M^2+1}: & & w_{M^2+1}, r_{N-N/M+1,M^2+1}, \ldots, r_{N,M^2+1}
\end{array}
$$

By decomposing this execution into layers, we can inductively quantify the metadata required to process it. Let e_1 be the execution fragment containing all write requests and only the read requests of R_1. Let e_i contain the requests of e_{i-1} plus all read requests of R_i, for $i = 2, \ldots, N$. Thus $e_N = e_*$.

Lemma 3. *Processing e_k while satisfying N+O+S requires $\Omega(kM^2)$ metadata, for $k = 1, \ldots, N$.*

Proof Summary. The proof is by induction. For the base case of e_1, Lemma 2 requires us to transfer $R_1 \rightarrow w_1$ from S_1 to all $M-1$ servers targeted by R_1. We show that the write protocol cannot efficiently transfer this metadata, since it does not know which servers R_1 targets, and hence must send $R_1 \rightarrow w_1$ to all M^2 servers, or $\Omega(M^2)$ metadata. Alternatively, $r_{1,1}$ can convey the list of target servers, but due to asynchrony, a different execution could cause a different target server S_j to play the role of S_1, making it impossible to know which $r_{1,j}$ will appear before a write. Thus, every $r_{1,j}$ must include the list of M servers, requiring $\Omega(M*M) = \Omega(M^2)$ metadata. In the inductive step, we show that e_k cannot rely on previous metadata transferred in e_{k-1}, and thus requires an additional $\Omega(M^2)$ metadata. ■

Completion of the proof. By Lemma 3, $e_* = e_N$ requires $\Omega(NM^2)$ metadata. Since $R_1, \ldots, R_N$ issue NM read requests total, the amortized metadata required per read request is $\Omega(\frac{NM^2}{NM}) = \Omega(M)$, which is not constant, violating C. ■

4.2 The Broad Scope of NOCS

We prove NOCS is impossible in the specific setting of one-shot read-only transactions in failure-free systems. When it comes to an impossibility result, the more restricted the setting it is proved in, the stronger the result, because any setting that is more general is also subject to the impossibility result (the general setting *includes* the restricted setting as a special case). Thus, the NOCS Theorem also applies to more general settings, such as those with read-write transactions, multi-shot transactions, and/or failures.

4.3 NOCS Is Tight

While all properties are impossible to achieve together, we find that NOCS is "tight" in the sense that any combination of three properties is possible. Spanner's [11] read-only transactions are one-round, use constant metadata, but block reads in order to return strictly serializable results (O+C+S). Many systems use multiple non-blocking round trips to coordinate strongly consistent results (N+C+S), e.g., DrTM [55], RIFL [34]. To the best of our knowledge, no existing system provides strict serializability in one round of non-blocking communication (N+O+S). We present the design of such a system, PORT-SEQ, and a proof of its correctness in Appendix D. The design uses a centralized write sequencer to totally order writes, and requires a linear amount of metadata for read-only transactions. We are aware of two systems that have performance-optimal read-only transactions (N+O+C): MySQL Cluster [45] and the snapshot read API of Spanner. These systems provide weak consistency, however, as we discuss below.

5 NOCS Connects Theory with Practice

This section discusses the value of the NOCS Theorem in understanding the design space and in guiding system designs.

5.1 Theoretical Insights

Proving the impossible. NOCS is philosophically similar to other impossibility results like CAP and SNOW, in that it helps system designers avoid attempting the impossible and instead identifies a fundamental choice they must make: their system can either have performance-optimal read-only transactions or provide strict serializability, but not both.

Identifying the possible. The crux of NOCS's impossibility is that the real-time requirement of strict serializability forces read-only transactions to confront conflicting requests (Lemma 1). This suggests optimal performance could be possible with even *slightly* relaxed consistency models that do not require real-time ordering, and thus can avoid the unstable region. In particular, the second strongest consistency model we are aware of—process-ordered serializability [39]—does not require real-time ordering.

Yet, there is a large gap in the current design space. The only two existing systems whose read-only transactions are performance optimal provide weak consistency. MySQL Cluster's read-committed consistency does not isolate transactions. Spanner's snapshot read API can be used to get performance optimality, but it does not ensure clients see their own recent writes when used in this way (§10). Between these weak guarantees and strict serializability are many stronger consistency models, such as read-atomic [6], causal consistency [36], and process-ordered serializability [39]. We bridge this gap by presenting the PORT design that provides performance-optimal read-only transactions and the strongest consistency to date: PORT provides process-ordered serializability in systems with only simple writes (§6), and it provides causal consistency in systems with write transactions (§8). (We conjecture causal consistency is the upper bound for performance-optimal read-only transactions when transactional writes are present.)

PORT implies that performance-optimal read-only transactions are possible with any consistency model equal to or weaker than what PORT provides. Recent work concurrent to ours presented a conflicting theorem that implies performance-optimal read-only transactions are impossible with causal consistency in systems with simple writes [14]. Appendix E discusses the claim and its relation to our results.

5.2 Guiding System Designs

NOCS is also useful in guiding system designs. First, to make a design performance-optimal, it must satisfy the NOC properties: each transaction must succeed using a single round of non-blocking messages with constant metadata. Therefore, the NOC properties indicate we must avoid validation-based and stabilization-based techniques to satisfy O, avoid techniques based on distributed lock management to satisfy N, and ensure the complexity of processing a read does not depend on the level of contention—i.e., the number of conflicting reads and/or writes—to satisfy C. Second, the NOCS Theorem suggests a path towards designing NOC protocols by avoiding how it derives its impossibility: read-only transactions should always execute on system states outside the unstable region. These implications of the NOC properties and the NOCS proof significantly reduced the design space of algorithm we needed to explore and led us to two high-level techniques for PORT: explicit ordering control and multi-versioning.

Explicit ordering control. There are two methods for ensuring reads avoid the unstable region by explicitly controlling the ordering of concurrent operations. First, reads can request versions of the data that lie before the unstable region begins, which orders a read-only transaction before ongoing writes. Second, servers can reorder operations when a read requests data in the unstable region.

Explicitly controlling ordering is not compatible with strict serializability because the real-time requirement forces a specific ordering of operations (Lemma 1) that cannot be communicated in a performance-optimal system (Lemma 3). Consistency models without the real-time requirement, however, might be compatible with an explicitly controlled ordering while satisfying NOC. PORT confirms this, by using versions clocks to capture this explicit ordering. PORT uses both types of explicit control on top of multi-versioning to provide its consistency guarantees and optimal performance.

Multi-versioning. Enabling reads to control what version of data they request requires multi-versioning on servers. Multi-versioning introduces storage overhead to temporarily keep additional version around, but this overhead is minor as storage is inexpensive and extra versions are not kept long. It also introduces some processing overhead to look up the correct version of data to return, reflected by our C property.

The need for multi-versioning to support efficient reads is not new. The existing performance-optimal systems, Spanner and MySQL Cluster, are multi-versioned. In fact, all existing systems whose read-only transactions are guaranteed to terminate—i.e., have a bounded number of retries and/or bounded blocking—are multi-versioned (Table 11). On the other hand, multi-versioning alone does not ensure optimal performance: most MVCC protocols require either extra on-path messages to query a timestamp oracle [7, 49], off-path messages to compute stable snapshots [4, 16], or blocking reads if the client-provided timestamp in MVTSO-based protocols points to the future [35, 51]. PORT's novelty is in how it uses version clocks to explicitly control ordering by manipulating the multi-versioning framework in order to achieve optimal performance.

6 PORT Design

PORT is a new system design that enables performance-optimal read-only transactions with process-ordered serializability, the strongest consistency to date.

Process-ordered serializability. Process-ordered serializability guarantees there exists a legal total order of transactions that respects the ordering of transactions within each process [39]. It is equivalent to sequential consistency [32] with the addition of transactional isolation. It preserves all the properties of strict serializability (§4) except for the real-time order across processes (clients). That is, it preserves the real-time order within each process, i.e., process order, and a total order across processes, but a client may not see the most recent updates of other clients. *Process order* ensures that each client interacts with the system monotonically, e.g., sees her own recent writes. *Total order* ensures that concurrent transactions are observed by all clients in the same order.

6.1 Version Clocks

This section describes *version clocks* (§6.1), a new specialized logical clock that tightly couples all the components of PORT (§6.2). Version clocks also allow us to avoid the work of applying some writes (*write omission*, §6.3) and limit the

```
1 Client Side
2 versionstamp = 0 # clock value
3 view[]           # max known versionstamp per server
4
5 # Sending requests
6 function get_vs_read():
7   versionstamp = tick(min{view[]}) # stable frontier
8   return versionstamp
9
10 function get_vs_write():
11   versionstamp++
12   return versionstamp
13
14 # Receiving a response msg from server svr
15 function recv_response(maxVS):
16   view[svr] = max{view[svr], maxVS}
17   if msg.for_write is true
18     versionstamp = tick(maxVS)
19   return
20
21 function tick(vs):
22   return max{vs, versionstamp}
23
24 Server Side
25 maxVS = 0 # max seeen versionstamp
26 # ... return maxVS when sending response msg
```

Figure 1: Pseudocode for version clocks.

staleness of reads (*data freshness*, §6.4).

Version clocks are designed in the context of distributed storage systems and have two features: they ensure process order by concisely capturing the ordering constraints between requests and enable optimal performance by reading at the most recent snapshot in the stable region.

Enforcing process order. Version clocks take advantage of two observations. First, process order is a per-client order, and thus can be explicitly controlled by clients. Second, read and write requests have different semantics, i.e., writes modify system state while reads do not. Therefore, they should be treated differently: it is unnecessary to enforce an order among the read requests that observe the same system state.

Capturing the stable frontier. Version clocks follow the practical guidance of the NOCS Theorem (§5.2) to avoid the unstable region by capturing the stable frontier. The stable frontier is the most recent snapshot in which all writes are in the stable region. Each server tracks the final versionstamp of its most recent write. A version clock tracks the minimum of such versionstamps across all servers the client has contacted, which is exactly the stable frontier the client knows. Version clocks direct read messages to the stable frontier when possible. PORT takes care of the cases when reads have to confront conflicting requests beyond the stable frontier. "Promotion" is used in systems with simple writes to advance the stable frontier beyond the versionstamp of an incoming read to ensure a total order. "Per-client ordering" is used in systems with write transactions to logically move a client's own writes before the stable frontier so the client can always safely read at the stable frontier (§8.3). Both techniques enforce the necessary order between concurrent reads and writes without blocking either reads or writes.

```
1 Client Side
2 function read_only_txn(<keys>):
3   vs = VersionClock.get_vs_read()
4   for k in keys # in parallel
5     vals[k], maxVS = read(k, vs)
6     VersionClock.recv_response(maxVS)
7   return vals   # replies to end user
8
9 function write(key, val):
10   vs = VersionClock.get_vs_write()
11   maxVS = write(key, val, vs)
12   VersionClock.recv_response(maxVS)
13   return        # replies to end user
14
15 Server Side
16 vers[keys][] # multi-versioned storage
17 function read(key, vs):
18   if vers[key][vs] exists
19     return vers[key][vs], VersionClock.maxVS
20   else # return nearest version to not block
21     near_vs = find_nearest_earlier(ver)
22     # ensure future writes have higher vs
23     vers[key].max_r_vs = max(vers[key].max_r_vs, vs)
24     return vers[key][near_vs], VersionClock.maxVS
25
26 function write(key, val, vs):
27   if vs <= vers[key].max_w_vs
28     return VersionClock.maxVS # omit write
29   if vers[key].max_r_vs >= vs
30     vs = max_r_vs + 1 # commit after promoted versions
31   vers[key][vs] = val
32   vers[key].max_w_vs = vs
33   if vs > VersionClock.maxVS
34     VersionClock.maxVS = vs
35   return VersionClock.maxVS
```

Figure 2: Pseudocode for PORT.

Clock structure. Figure 1 shows the pseudocode of version clocks. *versionstamp* stores the current clock value (line 2), which is embedded in every read/write message to explicitly control their ordering. When versionstamps are the same for two operations of the same type, the server orders them arbitrarily. When versionstamps for a read and a write are the same, the server orders the read after the write. A server responds with the highest versionstamp it has seen (line 26). A client uses *view* to track the highest versionstamps of the servers it has contacted (line 3) and uses them to find the stable frontier (line 7) before sending a read message (lines 6–8). *view* is updated upon receiving a response (line 16). If the response is for a write message, then the clock is advanced so that future read messages will have greater versionstamps than the write (lines 17–18), ensuring read-your-writes. Because versionstamps increase monotonically and reads have non-smaller versionstamps than earlier writes, version clocks preserve process ordering.

6.2 Basic PORT Design

The basic PORT design includes a multi-versioning framework, a read-only transaction algorithm, and a write algorithm. We co-design these components tightly by leveraging version clocks. Figure 2 shows PORT's pseudocode.

Client library. The read-only transaction and write algorithms are executed by a client library. For each read-only transaction or write, the client obtains a versionstamp from

its version clock and embeds it in the request message(s). This per-client versionstamp decides which system version on the servers the operation must read (or write) to ensure the client's process order (lines 3, 10). The server-side logic ensures a total order on top of the process order on each client to guarantee process-ordered serializability.

Multi-versioning framework. Servers store written values in a multi-versioning framework (line 16). Since PORT uses version clocks to track the ordering between operations, it is natural and efficient to index the historical values of each data item with versionstamps. In this way, the multi-versioning framework and transaction layer are nicely coupled via versionstamps. We omit a detailed discussion of garbage collection, which uses standard mechanisms similar to those used to provide at-most-once semantics.

Read-only transactions. To process a read request, a server executes it against the system version specified by its versionstamp. Executing a read is thus equivalent to returning the value indexed at versionstamp. If the server has the requested version, then the read is inside the stable region and it returns the version directly (lines 18, 19). Otherwise, it uses promotion to ensure a total order between the read and any concurrent writes at the specified versionstamp, without blocking either the read or write (lines 20–24).

Promotion logically copies the value of the nearest earlier version to all empty positions between that version and the one requested by versionstamp. Logical versions are used as placeholders to ensure a total order: once a version has been read by any client, no earlier versions can be modified to ensure different clients observe them in the same order. For example, if a read request has $vs = 4$ and the data item has committed values at $vs = 1, 2$, the version at $vs = 2$ is the nearest earlier version and is promoted to positions $3, 4$. A conflicting write at $vs = 3, 4$ will be "bumped up" to $vs = 5$ when it arrives. We implement promotion with a single variable (line 23) that marks earlier positions as immutable.

Writes. When receiving a write request, a server finds the position specified by the write's versionstamp in the multi-versioning framework. If the position is empty, then the write is applied at the versionstamp (line 31). If the position has been marked immutable by read promotion, the server finds the next available position to write the version at (lines 29–31). The write protocol also includes a mechanism for safely skipping concurrent writes (lines 27–28), discussed next.

6.3 Write Omission

Write omission is a special conflict resolution mechanism that skips an incoming write if it is concurrent with an already applied write. Omitting a write is desirable because it saves the computation needed to apply it, reduces the number of stored versions, and saves the work of replicating it.

Write omission is safe. Consistency models in general, and process-ordered serializability specifically, allow conflicting writes to be ordered either way. For instance, if two processes concurrently issue w_1 : `write(x = 1)` and w_2 : `write(x = 2)`, then they can be ordered as either (w_1, w_2) or (w_2, w_1). Typically, systems apply writes in the order that they arrive, e.g., w_1 then w_2. But if instead we use the opposite order, then this is equivalent to omitting w_2, as shown in Figure 3: skipping the later write is equivalent to ordering it before the earlier write and immediately overwriting it with the latter. Write omission does not affect the total order requirement: all clients observe concurrent writes in the same order, because omitted writes are never seen by any client.

Knowing a write is concurrent. Version clocks enable PORT to identify when writes are concurrent, allowing a later concurrent write to be omitted. PORT omits an incoming write if its versionstamp, vs_{omit}, is less than or equal to the highest committed versionstamp of the data item, $vs_{highest}$ (lines 27–29). The write with the highest committed versionstamp cannot have happened-before [31] the omitted write because $vs_{highest} \geq vs_{omit}$. More specifically, version clocks guarantee the invariant: if write x happens-before write y, then $vs_x < vs_y$. The omitted write cannot have happened-before the write with the highest committed versionstamp because it has not happened yet. Therefore, the two writes are concurrent, and it is safe to omit the incoming write.

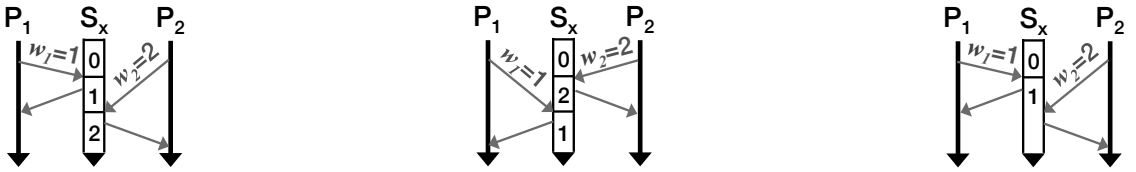
Omitting a write is equivalent to applying it immediately before the write with the highest versionstamp. A client's future reads must observe the "higher" write if its own write was overwritten in this way. Therefore, the server returns the versionstamp of its highest applied write to the client (line 29), which uses it to update its versionstamp as normal.

6.4 Keeping Reads Fresh

To avoid the unstable region, we must sometimes return values staler than what strict serializability would return (§5.2). PORT limits data staleness in two ways, neither of which incurs extra messages, blocking, or non-constant metadata. That is, they do not forfeit optimal performance (NOC).

Reducing staleness with version clocks. Instead of naively returning versions far behind the stable frontier, version clocks try to track the stable frontier precisely. They use *view* to track the most recent versionstamp on each server a client has contacted, so a client's version clock never ticks slower than the servers it is aware of. This significantly improves the freshness of data requested by read-only transactions.

Reducing staleness via co-location. Many storage systems co-locate "end users" on the same client machine [13, 19, 46], i.e., each client (machine) has many sessions (threads), one per end user. We leverage co-location to help user sessions keep each other fresh by sharing one version clock among them on the same client, which ensures no user session is staler than the freshest session it is co-located with.



(a) orders w_1 before w_2 by arrival. **(b) orders w_2 before w_1 by arrival.** **(c) orders w_2 before w_1 by omission.**

Figure 3: Space-time diagrams showing three executions of writes w_1 and w_2 that are concurrent and conflicting. The value underneath S_X indicates the value stored by the server. Process-ordered serializability allows w_1, w_2 to be ordered either way. This enables us to omit w_2 in (c) because it is equivalent to the ordering in (b), i.e., (w_2, w_1).

6.5 Correctness and Generality

The only technique PORT relies on is version clocks, which can easily be added to systems with existing physical/logical clocks, or implemented from scratch. We demonstrate both by applying PORT to a system without transactions (shown by Scylla-PORT) and a system with existing sub-optimal read-only transactions (shown by Eiger-PORT). We present a proof of correctness for PORT in Appendix B.

Failures. PORT can tolerate server failures using typical techniques such as state machine replication [52]. To tolerate client—i.e., frontend—failures, clients can send versionstamps back to end-user machines that then include the versionstamp in subsequent requests to the application (e.g., via cookies). This ensures process ordering is maintained even if an end user's later requests go to a different frontend due to load-balancing or frontend failure.

7 PORT Implementation and Evaluation

This section discusses Scylla-PORT, the implementation of PORT on a clean slate base system.

7.1 Implementation

We build PORT on ScyllaDB [53], a clean slate, non-transactional base system that supports only simple reads and simple writes. ScyllaDB is a production system that serves as a drop-in replacement for Cassandra [30] and provides an order-of-magnitude better performance. It is well-engineered and aggressively-optimized for performance, including a new implementation in C++14, core-level sharding that avoids cross-core locking and context switches, and customized lock-free data structures.

Rationale and takeaways. We chose to implement PORT on ScyllaDB for three reasons. First, it stresses the efficiency of PORT: as a highly efficient baseline system, it is sensitive to any additional overheads, and thus amplifies any performance cost introduced by PORT. Second, ScyllaDB is single-versioned. The negligible performance overhead shown in our evaluation includes the cost of making it multi-versioned (§5.2), which shows the efficiency of co-designing the multi-versioning framework and the transaction layer enabled by version clocks. Third, PORT is compatible with all the customized engineering decisions of ScyllaDB, which demonstrates the generality of the design of PORT.

7.2 Evaluation Overview

We evaluate Scylla-PORT against ScyllaDB (the clean slate, non-transactional base system) and Scylla-OCC (an implementation of OCC atop ScyllaDB). We compare their throughput, latency, scalability, and quantify data staleness.

Scylla-OCC. We implemented a variant of OCC optimized for read-only transactions, similar to Rococo's read-only transaction algorithm [43]. It includes an initial round of optimistic reads and then a validation round. If the values read in the optimistic round match the values in the validation round the transaction succeeds. If not, the read-only transaction is aborted and retried. This variant has strictly better performance than traditional distributed OCC because it avoids the need for distributed commit: its best case is two rounds compared to traditional distributed OCC's best case of three rounds (read, validate/prepare, commit).

Code. We implemented our server-side logic in ScyllaDB's codebase (release 2.1-RC3) in C++14 and our client-side logic in the Java Thrift client of the YCSB benchmark (release 0.10.0) [10]. Version clocks are implemented on both servers and clients. Scylla-PORT adds ~1,300 LOC.

Experimental setting. We run experiments on Emulab [56]. Each machine has two 2.4 GHz 8-Core Xeon CPUs, 64 GB RAM, and a 10 Gbps network interface. We use a single datacenter setting. All experiments, except for scalability tests, use 8 servers loaded by 8 client machines. The scalability tests use up to 64 machines. Each client issues 10 million requests in each experiment, which takes 5–10 minutes to complete, sufficiently long to minimize warm-up and cool-down effects and provide stable results. Experiments are CPU-bound on servers.

Configuration and workloads. We use YCSB's standard workloads B (read-heavy, 95% reads) and C (read-only) with customized read-to-write ratios of up to 25% writes. We use YCSB's default parameters: 1 million records, 10 fields per record, 100 B values per field, and Zipf constant of 0.99. Each request (a read-only transaction or a group of simple writes) accesses 5 records and all fields in each record.

Results summary. Transactional overhead is generally evident with read-write conflicts and under skewed workloads,

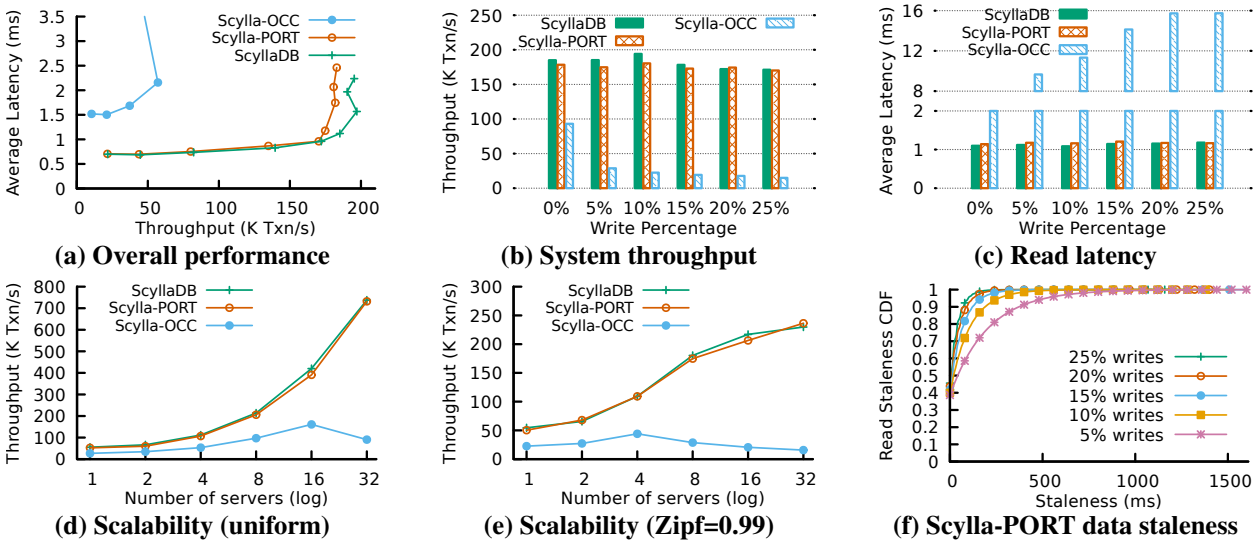


Figure 4: The performance of Scylla-PORT closely matches non-transactional ScyllaDB and is significantly better than OCC, Scylla-PORT scales even better than ScyllaDB with skewed workloads, and half of its reads return fresh data.

so we focus our evaluation in such scenarios to amplify Scylla-PORT's cost. Our results show that Scylla-PORT can almost match its performance to that of non-transactional ScyllaDB: 1–3% overhead in throughput and latency in most settings and less than 8% even in the worst case. Scylla-PORT outperforms OCC by an order-of-magnitude in such contended scenarios due to OCC's retries, and outperforms OCC under low contention (OCC's best case) by at least two times. Scylla-PORT scales as well as ScyllaDB and scales better under contention. More than 40% of its reads return fresh values.

7.3 Throughput and Latency

Figure 4a shows the overall performance of the systems as we gradually increase the system load by using more closed-loop client threads. Scylla-PORT has similar performance to the baseline ScyllaDB. Their largest difference before ScyllaDB becomes overloaded is evident with 32 client threads: 5.6% in throughput and 5% in latency. All later experiments report throughput and latency at this operating point, i.e., with 32 client threads. OCC initially has latency that is twice that of ScyllaDB and Scylla-PORT because it takes at least two rounds to complete instead of one. As load increases, OCC's latency increases quickly and its throughput decreases slightly because contention forces it to retry.

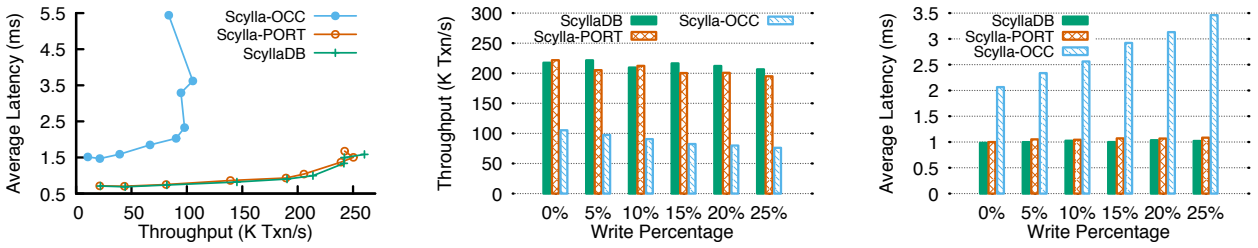
Varying write percentage. Figure 4b and 4c show the throughput and latency as we vary the read-to-write ratio. Scylla-PORT's throughput is within 4% of ScyllaDB's for five of the experiments and within 7% for the remaining one. Similarly, its latency is within 2% (20 µs) of ScyllaDB's for two of the experiments and within 7% (107 µs) for the other four. As the write percentage increases, the overhead disappears because of write omission: doing slightly more work during reads is offset by doing less work during writes. When there are only reads, Scylla-PORT has double the throughput and half the latency of OCC because OCC's read-only transactions require at least two rounds. With writes, OCC's performance drops quickly due to retries.

7.4 Scalability

Figure 4d compares the scalability of the three systems under a uniform workload as we increase the number of servers while increasing the number of clients to keep the servers CPU-bound. Scylla-PORT scales as well as ScyllaDB; the differences in throughput are negligible. Interestingly, Scylla-PORT outperforms ScyllaDB under a skewed workload, as shown in Figure 4e. ScyllaDB stops scaling at 16 servers because the server holding the hottest keys becomes the bottleneck, and adding more servers does not help. (We have confirmed this finding with ScyllaDB's developers.) Scylla-PORT scales better than ScyllaDB under skewed workloads because it can avoid the work of some writes to the hottest keys due to write omission. Since write omission only applies to conflicting writes, this rarely occurs under a uniform workload. OCC initially shows a similar scaling pattern starting from its lower throughput. OCC's scaling stops, however, as more concurrent clients accessing the same keys lead to higher contention and thus more retries.

7.5 Data Staleness

Figure 4f shows the staleness of Scylla-PORT under a skewed workload with varying write percentages. Staleness is measured relative to strict serializability, which always has a staleness of 0: it is the amount of time since a newer version has been committed. For example, if v_0, v_1 are consecutive versions, v_0 is returned at 0:05, and v_1 committed at 0:00,



(a) Overall performance (b) System throughput (c) Read latency

Figure 5: Performance of ScyllaDB, Scylla-PORT, and OCC under uniform workloads. Scylla-PORT matches almost exactly the performance of ScyllaDB and outperforms OCC by at least double the throughput and half the latency.

then the staleness of v_0 is 5 seconds.

Scylla-PORT returns the most recent data ~40% of the time, and 90% of reads return values no staler than 500 ms. Scylla-PORT returns fresher data as the write percentage increases because version clocks advance versionstamps more frequently when there are more writes. Scylla-PORT leverages version clocks to precisely capture the stable frontier, but does not utilize client co-location. Sharing one clock among co-located user sessions would further decrease staleness, but also decreases the rate at which write omission can be used. We leave investigating this tradeoff to future work.

7.6 Low Contention Evaluation

High contention workloads are where any differences between Scylla-PORT and ScyllaDB would appear. Scylla-OCC did poorly under high contention as is expected because OCC is better suited to low contention settings. Figure 5 presents the evaluation results of comparing the three systems under uniform workloads. These uniform workloads have low contention and thus mostly keep OCC in its best case. Figure 5a shows the throughput and latency of the systems as we increase the system load. Scylla-PORT has almost the same performance as ScyllaDB due to low contention as we expect. OCC has worse performance because it requires at least two round trips even under low contention, and its performance drops, i.e., lower throughput and higher latency, when there is more contention due to increased system load with 5% writes.

Figure 5b and Figure 5c show the throughput and latency when varying the read-to-write ratio. When there are only reads, Scylla-PORT has twice the throughput and half the latency compared to OCC due to the fact that read-only transactions with OCC require at least two rounds: optimistic reads and then validation, while Scylla-PORT can always finish in one round. When there are more writes, OCC's performance starts degrading due to read-write conflicts, while Scylla-PORT can always closely match its performance with the non-transactional baseline.

8 Improving an Existing System

This section adapts PORT to improve Eiger, an existing system that has both read-only and write transactions.

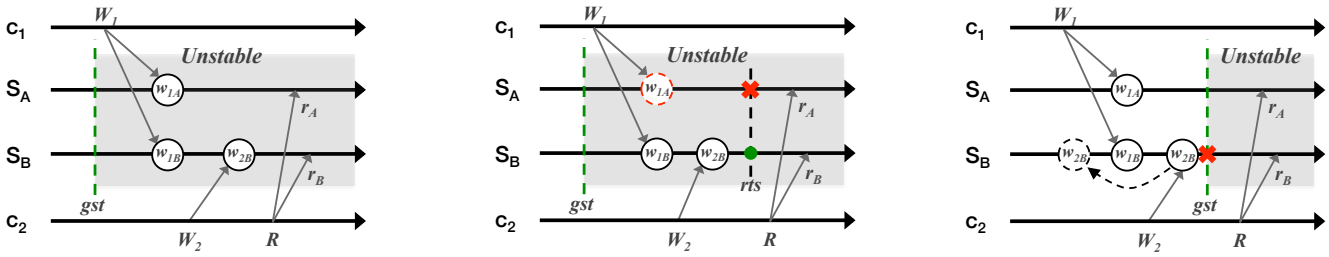
8.1 Eiger Overview and Rationale

Eiger is a geo-replicated, causally consistent system that has read-only transactions and write transactions. Each machine implements a Lamport clock and attaches a Lamport timestamp to each committed write that is guaranteed to be larger than any earlier write it causally depends on. Eiger's write transaction protocol is a variant of two-phase commit [24, 33] that always commits. Eiger's read-only transaction protocol takes between one and three non-blocking rounds of communication. If there are no concurrent write transactions, it completes in a single round. Otherwise, it requires a second round of messages to a subset of the servers, followed by a third round if the concurrent write transactions are still pending when the second-round requests arrive. In the third round, each read request needs to query the states of all write transactions it conflicts with, and thus the required metadata increases linearly with respect to the number of conflicting write transactions.

Rationale. We choose Eiger as a base system because of its guarantees and the efficiency of its read-only transactions. First, it provides causal consistency, not strict serializability, so it may be possible to add performance-optimal read-only transactions to it. Second, it includes write transactions, which present a new challenge for the PORT design. Third, it is the only system with write transactions and causal (or stronger) consistency that completes read-only transactions in a bounded number of non-blocking rounds of communication (Figure 11). Finally, its read-only transactions often complete in a single non-blocking round, making them a more difficult baseline than other algorithms such as OCC.

8.2 Design Challenges

The main challenge in making Eiger's read-only transactions performance optimal, which did not exist in basic PORT, is to ensure write isolation when a client has to read beyond the stable frontier, e.g., to read her own recent writes. Figure 6 shows some challenging scenarios. There are two servers, S_A



(a) Ensures read-your-writes (b) Ensures write isolation (c) Ensures process order

Figure 6: Example executions that show the challenges in making read-only transactions performance-optimal in the presence of write transactions. The challenges include ensuring read-your-writes, write isolation, and the process order.

and S_B, and two clients c_1 and c_2. W_1 is a write transaction by c_1. W_2 is a single key write transaction by c_2. R is a read-only transaction by c_2 reading two servers. The shadow areas represent the part of system history beyond the stable frontier, i.e., the unstable region.

Figure 6a shows the case in which R must read beyond the stable frontier, i.e., cannot use *gst* as the read timestamp, because otherwise c_2 would not see her own recent write, W_2. Figure 6b shows that using *rts* as the read timestamp does not work either, because it would violate write isolation of W_1, when w_{1B} has committed but w_{1A} has not (the commit message from the coordinator is delayed). That is, R would return a system state after w_{1B} on S_B, but a system state before w_{1A} on S_A. To avoid blocking and/or extra metadata, our solution is to use *rts* as the read timestamp on S_B, and *gst* as the read timestamp on S_A. This solution is equivalent to ordering c_2's writes, e.g., W_2, before all other conflicting writes by other clients, e.g., W_1. That is, c_2 reads W_2 and then W_1. Note that other clients would still see W_1 and then W_2, but this is allowed by causal consistency because it does not require a total order. By leveraging this flexibility, c_2 effectively "pulls" its recent write W_2 to its *gst*, and thus avoids reading in the unstable region. However, this solution yields another challenge, as shown in Figure 6c. When the global safe time *gst* moves forward and passes w_{2B}, c_2 should not return w_{2B} again in order to ensure process order, because c_2 has already seen w_{2B} before w_{1B}.

aren't rts and gst the same??

8.3 Eiger-PORT

Eiger's read-only transactions are non-blocking, require up to three rounds of on-path communication, and use linear-sized metadata in the third round. We make them performance-optimal by making them always finish in one round using only constant metadata. The major challenge is to ensure write isolation, i.e., return a system state that is either before all updates in a write transaction or after.

More specifically, when a read-only transaction must read beyond the stable frontier, e.g., to ensure read-your-writes, PORT reorders the read-only transaction and the conflicting writes without blocking by using "promotion" (§6.2). However, promotion does not work for Eiger because it cannot

```
1  Client Side
2  lst_map[][]    # maps server to its local safe time
3  gst            # global safe time
4
5  function read_only_txn(<keys>):
6    gst = get_read_ts(min{lst_map.valueSet()})
7    for k in keys  # messages in parallel
8      vals[k], lst = read(k, gst, cl_id)
9      lst_map[k.server] = lst # lst is monotonic
10   return vals
11
12 function write_txn(<keys, vals>):
13   for k, v in <keys, vals>  # in parallel
14     if k.server is coord # the coordinator
15       lst = write_coord(k, v, cl_id, gst)
16     else # a cohort
17       lst = write_cohort(k, v, cl_id, gst)
18     lst_map[k.server] = lst # lst is monotonic
19   return
20
21 function get_read_ts(ts):
22   return max{ts, gst}
```

Figure 7: Client-side pseudocode for Eiger-PORT.

ensure that all writes in the same write transaction are promoted at the same time since they can be on different servers. Our solution, *per-client ordering*, enables clients to observe conflicting writes in different orders, as allowed by causal consistency. Specifically, it pulls back any of a client's recent writes that are beyond the stable frontier. This allows the client to read at the stable frontier while also always seeing their own writes. Figures 7, 8, and 9 show the pseudocode, written in a way that favors clarity over efficiency.

Client-side logic. Figure 7 shows the client-side logic. Each client maintains two variables (lines 2, 3). *lst_map* tracks the local safe time, *lst*, of each server. Global safe time, *gst*, is the minimum *lst* across all servers (line 6) and advances monotonically. *gst* is used as the read timestamp for each read-only transaction. Both *lst* and *gst* are Lamport timestamps as used in Eiger. A client sends all read requests in a read-only transaction in parallel. Each read request includes the key, the read timestamp *gst*, and the unique identifier of this client (line 8). The server responds with the requested value and *lst* on that server. A client issues a write transaction by sending the write requests in parallel (lines 12–19). One server is randomly chosen as the coordinator (line 14)

```
1  Server Side (Read-Only Txn)
2  lst              # local safe time, updated upon writes
3
4  function read(k, rts, cl_id):
5    ver = DS[k].at(rts) # vers are sorted by commit_t
6    for v in DS[k].newer_than(ver.commit_t)
7      # ensure read-your-writes, from newer ver to old
8      if v.cl_id == cl_id and ver.commit_t <= v.gst <= rts
9        return v.val, lst
10   if ver.cl_id != cl_id
11     return ver.val, lst
12   else # ensure write isolation
13     v = find_isolated(ver)
14     return v.val, lst
15
16 function find_isolated(ver):
17   # iterate from newer version to old
18   while v in DS[k].newer_than(ver.gst)
19     and v in DS[k].older_than(ver.commit_t)
20     if v.cl_id != ver.cl_id
21       return v
22     else
23       return find_isolated(v)
24   return ver
```

Figure 8: Read-only transaction logic for Eiger-PORT.

for 2PC with the others as cohorts. Each write request contains the key, the value, the client ID, and the client's current *gst* (lines 15, 17). *gst* specifies the stable frontier this write transaction causally depends on. The client updates *lst_map* after each read/write request (lines 9, 18).

Write transactions. Figure 9 shows the server-side logic of write transactions. When a server receives a write request, it records the current Lamport time (line 29) and creates a new pending version (lines 8, 19, 32, 33). *pending_wtxns* tracks ongoing write transactions by keeping an ordered list of *pending_time*s. The running minimum of *pending_wtxns* is the *lst* on this server, i.e., no pending writes exist before *lst*. Because Lamport clocks advance monotonically, insertion, removal, and fetching the minimum of *pending_wtxns* have a cost of O(1). At the end of the "prepare" phase of 2PC, each cohort sends a yes-vote message to the coordinator, which includes the *prepared_time* of this pending write transaction. *prepared_time* is guaranteed to be greater than *pending_time* by clock ticking (line 31).

To commit a write transaction, the coordinator calculates the commit time by taking the maximum across all *prepared_time*s (line 11) and then sends a commit message to the cohorts and commits its local pending version (lines 13, 14). When a cohort receives the commit message, it commits its local pending version (lines 25, 38) with the commit time (lines 24, 37). It then removes this write transaction's *pending_time* from *pending_wtxns* and updates *lst* (lines 39–43). The server returns its *lst* to the client upon commit. Eiger-PORT made minimum changes to Eiger's write transactions, i.e., the management of *pending_wtxns*.

Read-only transactions. The technique that makes Eiger-PORT's read-only transactions performance-optimal while providing causal consistency is to allow each client to have her own perceived ordering of committed writes on each

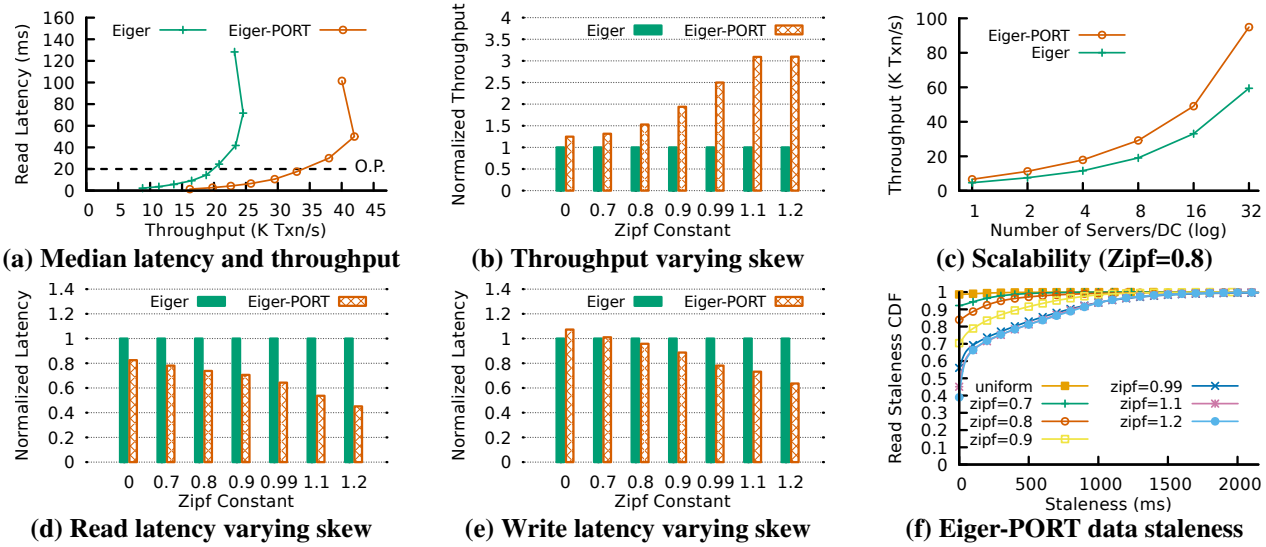
```
1  Server Side (Write Txn)
2  lst              # local safe time
3  pending_wtxns    # uncommitted write txns
4  DS[][]  # multi-versioned k-v data store
5
6  function write_coord(k, v, cl_id, gst):  # coordinator
7    # PREPARE
8    ver, prepared_t = prepare_write(k, v, cl_id, gst)
9    # ... get yes-vote-msgs from all cohorts
10   # COMMIT
11   commit_t = max{yes-vote-msgs.prepared_t, prepared_t}
12   commit-msg = {"commit", commit_t}
13   # ... send commit-msg to all cohorts
14   commit_write(ver, commit_t)
15   return lst
16
17 function write_cohort(k, v, cl_id, gst):  # cohort
18   # PREPARE
19   ver, prepared_t = prepare_write(k, v, cl_id, gst)
20   yes-vote-msg = {"yes", prepared_t}
21   # ... send yes-vote-msg to coordinator
22   # ... wait for commit-msg
23   # COMMIT
24   commit_t = commit-msg.commit_t
25   commit_write(ver, commit_t)
26   return lst
27
28 function prepare_write(k, v, cl_id, gst):
29   pending_t = LamportClock.current()
30   pending_wtxns.append(pending_t)
31   LamportClock.advance()
32   ver = DS[k].create_new_ver(v, cl_id, gst, pending_t)
33   ver.is_pending = true
34   return ver, LamportClock.current()
35
36 function commit_write(ver, commit_t):
37   ver.commit_t = commit_t
38   ver.is_pending = false
39   pending_wtxns.remove(ver.pending_t)
40   if pending_wtxns is empty
41     lst = LamportClock.current()
42   else
43     lst = pending_wtxns.head() # min of pending_wtxns
44   return
```

Figure 9: Write transaction logic for Eiger-PORT.

data object, and reading in her own perceived ordering enables optimal performance. More specifically, a client constructs her own perceived ordering on a data object as follows: ordering other clients' writes by their commit timestamp, which gives a partial order $\mathbb{O}$, and then inserting her own writes into $\mathbb{O}$ by comparing their *gst* with the commit timestamps of the writes in $\mathbb{O}$.

Figure 8 shows the server-side logic of read-only transactions. When a server receives a read request, it first finds the version at the read timestamp, *rts* (line 5), i.e., *ver* is the most recent version with $commit\_t \leq rts$. Then, client-perceived ordering is enabled by the server looking for a more recent version *v* written by the same client such that *v*'s *gst* is no less than *ver*'s *commit_t* and is no greater than *rts* (line 8).[1] The server breaks a tie between two versions with the same *gst* by their commit timestamp. If such a *v* exists, then the server returns *v* instead of *ver* to ensure read-your-writes (lines 6–9). If the version at *rts* was written by the same client, then we need to ensure write isolation by

[1]The second half of line 8 is newly added after the OSDI version to make client-perceived ordering more explicit.



(a) Median latency and throughput (b) Throughput varying skew (c) Scalability (Zipf=0.8)

(d) Read latency varying skew (e) Write latency varying skew (f) Eiger-PORT data staleness

Figure 10: Throughput, latency, scalability, and staleness of Eiger-PORT: up to 3× throughput improvement and 60% latency reduction compared to Eiger, better scalability, and low data staleness. All latencies are median latencies.

checking whether there exist any versions between the version's *gst*, which is the snapshot time the version depends on, and the version's *commit_t* (lines 18, 19). If there exists such a version written by a different client, then that version is returned to satisfy write isolation (lines 20, 21). We need to do this recursively, but our implementation uses a loop instead for better performance. To ensure write isolation (lines 16–24), we go through the multi-versioned data store once, which has the same cost as finding a particular version by timestamp in other algorithms, e.g., MVCC.

Correctness. We show the correctness of Eiger-PORT by proving that any execution in Eiger-PORT satisfies the causal ("happened before") relation [31] and write isolation for write transactions. We present the full proof in Appendix C.

9 Eiger-PORT Evaluation

We evaluate Eiger-PORT against Eiger, showing its throughput and latency improvement as well as its data staleness.

Implementation. We implemented Eiger-PORT as a modification to Eiger's code base, which is built on top of Cassandra [30] and written in Java. Eiger-PORT adds ~1000 LOC.

Experimental setting. We try to match Eiger's original experimental setup. We run all experiments on Emulab [56], similar to the now-decommissioned PRObE testbed [20] Eiger used. Each machine has one 2.4 GHz Quad-Core Xeon CPU, 12 GB RAM, and a 1 Gbps network interface. We run 5 trials for each data point, each lasting 65 seconds, and report the median. We exclude the first and last 15 seconds to avoid artifacts due to warm-up, cool-down, and imperfectly synchronized clients. All experiments are CPU-bound.

Configuration and workloads. We use the same setting as Eiger: two logical datacenters co-located in the testbed. Each datacenter has eight server machines, and uses eight client machines to load the servers. The second datacenter is used as a replica, which applies updates replicated from the first datacenter. We use the dynamic workload generator from Eiger with the same default values: 1 million keys, 128-byte values, 5 columns per key, 5 keys per operation, and a write percentage of 10% unless otherwise specified. We also use a Zipf traffic generator with a default value of 0.8.

9.1 Performance Improvement

Results summary. Eiger-PORT significantly improves the performance of Eiger under different workloads, without degrading write performance: 2× and 3× throughput improvement under mild and high skew, respectively, and 20%–60% latency reduction. The performance improvement comes from Eiger-PORT's fewer on-path messages and less metadata to process. The improvement is larger in contended workloads because Eiger is more likely to require more than one round and more metadata in the third round when there are more conflicting write transactions.

Throughput improvement. Figure 10a shows the median read latency and system throughput as we double the number of closed-loop client threads loading the system (from 2 to 512). It shows that Eiger-PORT performs strictly better than Eiger: it achieves higher throughput with the same latency and lower latency with the same throughput. We run all other experiments in Figure 10 with 32 threads, representing an operating point with reasonably low latency (< 20 ms), i.e., at line "O.P." in Figure 10a. The improvements are more profound at higher loads. Figure 10b shows normalized throughput with different skew; the improvement stops increasing after Zipf value 1.1, where a single server becomes the bottleneck. Figure 10c shows Eiger-PORT scales better than Eiger due to fewer messages in the system.

Latency improvement. Figure 10d shows the normalized median read latency as we vary skew. Eiger-PORT achieves 20% lower latency under uniform workloads and up to 60% lower latency under contended workloads. Figure 10e shows that Eiger-PORT achieves lower write latency even though we did not intentionally improve writes. The lower latency comes from less queuing delay for writes because reads are faster and there are fewer messages in the system. This demonstrates that PORT can make read-only transactions performance-optimal without making writes more costly.

9.2 Data Staleness

Figure 10f quantifies the read staleness in Eiger-PORT. Staleness is measured relative to strict serializability as in Scylla-PORT's evaluation. Even with high skew, over 40% of Eiger-PORT's read-only transactions return up-to-date values, and over 90% of reads experience less than 1 s staleness. Eiger-PORT tends to return staler data than Scylla-PORT because the stable frontier moves more slowly in Eiger/Eiger-PORT: write transactions take longer to commit than simple writes.

10 Related Work

This section examines existing read-only transactions with the NOCS Theorem, reviews impossibility results, and discusses the move from latency to performance optimality.

Bridging the gap in the design space. We use the NOCS Theorem as a lens to better understand existing systems and show a set of representative systems in Figure 11. We find a large gap in the design space. The only existing systems that have performance-optimal read-only transactions provide weak consistency (§4.3). MySQL Cluster [45] provides read-committed, which does not isolate transactions. Spanner's snapshot reads API [11] cannot always guarantee non-blocking read-your-writes. Suppose a client updates key k in a read-write transaction with commit timestamp ts, and then immediately performs a read-only transaction involving a set S of keys that includes k. To ensure read-your-writes, the client must use a timestamp greater than or equal to ts for its read-only transaction. But doing so may block since other keys in S may be involved in a read-write transaction that is in the midst of two-phase-commit with a commit timestamp less than ts. That is, Spanner must use its externally consistent read-only transaction API, which may block reads in such cases to ensure read-your-writes.

We bridge this gap in the design space with PORT, the first design that provides performance-optimal read-only transactions and the strongest consistency to date.

Other read-only transactions. Some systems choose to trade one performance property for stronger guarantees [1, 11, 34, 55] but still reside on the "tight boundary" of the NOCS Theorem. Many systems neither are performance-optimal nor provide the strongest possible guarantees [4, 6, 14, 16, 36, 37, 39, 41], and thus could potentially be improved by our PORT design.

System	N	O	C	S	W
Performance-optimal					
Scylla-PORT *	✓	✓	✓	POS	×
Eiger-PORT *	✓	✓	✓	Causal	✓
Spanner-Snap [11]*	✓	✓	✓	SR	✓
MySQL Cluster [45]*	✓	✓	✓	RC	✓
One fewer performance property for stronger guarantees					
Spanner-RO [11]*	×	✓	✓	✓	✓
DrTM [55]*	✓	≥ 1	✓	✓	✓
RIFL [34]	✓	≥ 2	✓	✓	✓
Sinfonia [1]	✓	≥ 2	✓	✓	✓
Candidates for improvement in performance and/or guarantees					
TAPIR [57]*	×	✓	✓	Ser	✓
Pileus-Strong [54]	×	2	✓	✓	✓
Rococo-SNOW [39]*	×	✓	Linear	✓	✓
COPS-SNOW [39]*	✓	Off-path	Linear	Causal	×
COPS [36]*	✓	≤ 2	Linear	Causal	×
RAMP-F|H [6]*	✓	≤ 2	Linear	RA	✓
RAMP-S [6]*	✓	2	✓	RA	✓
Eiger [37]*	✓	≤ 3	Linear	Causal	✓
Janus [44]	×	≤ 2	Linear	✓	✓
Callinicos [47]	×	2	Linear	✓	✓
Occult [41]	✓	≥ 1	✓	PC-PSI	✓
Rococo [43]*	×	≥ 2	✓	✓	✓
Contrarian [14]*	✓	2	✓	Causal	×
GentleRain [16]*	×	≤ 2 + off-path	✓	Causal	×
Cure [4]	×	Off-path	✓	Causal	✓
MVTSO [35, 51]	×	✓	✓	Ser	✓

Figure 11: A review of existing systems through the lens of NOCS. Asterisks denote specialized read-only transaction algorithms. W denotes write transactions.

Impossibility results. Our NOCS Theorem is philosophically similar to other impossibility results, e.g., FLP [18], CAP [8, 21], and SNOW [39], in that it saves system designers' effort from trying the impossible. The most relevant result is the SNOW Theorem, which we discuss next.

The move from latency to performance. SNOW [39] showed tradeoffs in the design space of read-only transactions with a focus only on latency. It proved optimal latency is impossible if the system is strictly serializable and has write transactions. This work aims for a more complete understanding of the tradeoffs in the design of read-only transactions by considering latency and throughput. The move from latency to performance has two takeaways.

First, optimal latency neither translates to nor forfeits optimal throughput. The former is shown by the two systems built with SNOW, which provided lower latency at the cost of lowering throughput. The latter is shown by our new designs that achieve both optimal latency and optimal throughput. What really matters is a complete understanding of the tradeoff between performance and consistency and its insights for designs—the major contributions of this work.

Second, higher demand for performance, e.g., the move from latency only to both latency and throughput, suggests higher difficulty in providing stronger guarantees. Optimal latency is possible in strictly serializable systems without

write transactions, but optimal performance is not.

11 Conclusion

Distributed storage systems rely on read-only transactions to provide consistent views of sharded data. Our NOCS Theorem proves that read-only transactions cannot have optimal performance in strictly serializable systems. We presented PORT, a performance-optimal read-only transaction design that provides the strongest consistency to date. We applied PORT to design Scylla-PORT and Eiger-PORT. Scylla-PORT has minimal performance overhead compared to its non-transactional baseline. Eiger-PORT significantly improves the performance of its transactional base system.

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A Proof of the NOCS Theorem

Note: This section is a complete version of §4, including full proofs of all lemmas and the main theorem. A substantial amount of text is repeated from §4 for completeness.

Our main result is that performance-optimal read-only transactions (N+O+C) cannot provide strict serializability (S).

The NOCS Theorem. *No read-only transaction algorithm satisfies all NOCS properties.*

System model. We model a distributed system as a set of processes that communicate by sending and receiving messages. This model is similar to that used in FLP [18]. A set of client processes (clients) issue requests to server processes (servers) that store the data. Processes are modeled as deterministic automata: in each atomic step, they may receive a message, perform (deterministic) local computation, and send one or more messages to other processes.

A transaction (operation) starts when a client sends the request messages to servers and ends when the client receives the last necessary server response. Two transactions (operations) are concurrent if their lifetimes overlap, i.e., neither begins after the other ends. If concurrent transactions (operations) access the same data item, then they conflict.

Assumptions. We make the following assumptions:

(A-0) There are ≥ 2 servers and ≥ 2 clients. Otherwise, optimal performance and strict serializability are trivial. All reads and writes eventually complete.

(A-1) The network and processors are reliable. Every message is eventually delivered and processed by the destination process. Processes are always correct and never crash. By proving our result under these restrictive assumptions, it will necessarily hold when system can fail.

(A-2) The network is either asynchronous [21], i.e., messages can be arbitrarily delayed, or partially synchronous [17], i.e., physical clocks ensure bounded delays.

Proof intuition. Due to network asynchrony, it is always possible for a read-only transaction to conflict with write operations and other concurrent read-only transactions. These requests occupy an "unstable" region in the system's history, where a total order has not yet been established. We show that the real-time order requirement of S requires read-only transactions that are N+O to return the most recently written

values (Lemma 1). Doing this while ensuring a legal total order, however, requires transferring metadata between the servers (Lemma 2), either proactively through read requests or through the write protocol. By extending this construction, we show that processing a set of read-only transactions requires metadata that is asymptotically larger than the total size of the transactions, regardless of how the metadata is transferred (Lemma 3). This violates C, proving the theorem.

Proof. Suppose the system has two servers, S_1 and S_2, and multiple clients. Let ALG be any read-only transaction algorithm that satisfies N+O+S. Let $R = \{r_1, r_2\}$ be a read-only transaction that executes ALG, issued by client C_R. Let w_1 and w_2 be simple write requests issued by client $C_w \neq C_R$, where $w_1 \to w_2$ in real-time, i.e., w_2 is sent after the response for w_1 is received. We place no restrictions on the write protocol (beyond assumption A-0). Consider the execution e_1:

S_1 : r_1, w_1
S_2 : w_2, r_2

Suppose there is no metadata in the system, i.e., no information for coordinating consistent values between requests.

Lemma 1. *Without metadata, a read-only transaction that is N+O+S must observe any write that precedes it at a server.*

Proof. Consider only w_2 and r_2 in e_1 (ignore all other operations). R satisfies N+O+S and is preceded by w_2 at S_2. We ensure w_2 is processed first by arbitrarily delaying r_2's arrival (assumption A-2). Assume (to contradict) that R does not observe w_2 in e_1. R and w_2 are issued concurrently by clients C_R and C_w; assume w.l.o.g. that C_w issues w_2 first at time t. Consider an alternative execution e_1' that modifies e_1 after t so that C_w receives the response for w_2 just before C_R issues R, requiring $w_2 \to R$. Since w_2 is issued before t, it is identical in e_1' and e_1. C_R is unaware of w_2's response—any communication related to it can be arbitrarily delayed—and there is no metadata in r_2. Thus r_2 is also unchanged. No further messages for R are received at S_2 because R is N+O. Since S_2 is a deterministic automaton that receives identical messages up to r_2 in both e_1 and e_1', its output is identical, i.e., R does not observe w_2 in e_1'. But this means that R violates S (since $w_2 \to R$), giving our contradiction. ■

Lemma 2. *Processing e_1 while satisfying N+O+S requires dependency $R \to w_1$ to be transferred from S_1 to S_2.*

Proof. Since R satisfies N+O, r_1 is processed before w_1 at S_1, creating the dependency $R \to w_1$. Assume (to contradict) that no metadata is transferred to S_2. Lemma 1 states that r_2 must observe w_2 at S_2, implying $w_2 \to R$. Since $w_1 \to w_2$ by construction, this creates a cycle, violating the legal total order of S. Thus, metadata must be transferred to S_2 to ensure that r_2 is executed prior to w_2 in the total order.

S_2 must therefore compute the function $f(R \to w_1, w_1 \to w_2) = R \to w_2$. Assume S_2 has $w_1 \to w_2$ as input; this can be conveyed by C_w through w_2, for example. Dependency $R \to w_1$ is only known by S_1 initially because r_1 and w_1 are issued concurrently, and thus their arrival order is only finalized at S_1. Since S_2 computes $f(x,y)$ with $x = R \to w_1$ as the input at S_1 and $y = w_1 \to w_2$ as its local input, a standard lower bound from two-party communication complexity implies $R \to w_1$ must be transferred to S_2 [29]. ■

Implication of Lemma 2. Since S_1 and S_2 are deterministic automata, dependency information like $R \to w_1$ must be transferred through metadata in messages. We call metadata that is unaware of the dependency *a priori*, and metadata that is aware of it *a posteriori*. Since r_1 and r_2 are issued concurrently with w_1, they are unaware of $R \to w_1$ and hence can only contain a priori metadata. (No further messages are possible for R because it is N+O.) In contrast, w_1 is processed after r_1, establishing $R \to w_1$, so any subsequent message in the write protocol may contain a posteriori metadata.

We now extend e_1 with more read-only transactions, servers, and write requests, and apply the structure above to force more dependency metadata to transfer between the servers. We then show that neither type of metadata transfer—a priori or a posteriori—can satisfy C.

Proof of the NOCS Theorem. Suppose the system has M^2+1 servers $S_1, S_2, \ldots, S_{M^2+1}$. Let $R_1, R_2, \ldots, R_N$ be N read-only transactions that execute ALG, where each R_i sends a read request to S_1 and $M-1$ other servers, such that every server other than S_1 receives N/M read requests. (In practice $M^2 \ll N$, but our construction works for any $N, M \geq 1$.) The specific mapping of read requests to servers is unimportant; we lay them out sequentially by transaction index below. Let $r_{i,j}$ be a read request of R_i assigned to S_j. We assign one read request from each of R_1 to $R_{N/M}$ to S_2, one read request from each of $R_{N/M+1}$ to $R_{2N/M}$ to S_3, and so on, restarting at R_1 after reaching R_N. Let $w_1, w_2, \ldots, w_{M^2+1}$ be M^2+1 simple writes issued to each server by a distinct client C_w that does not issue any read-only transactions. Suppose w_1 precedes all other writes, i.e., $w_1 \to w_j$ for $j = 2, \ldots, M^2+1$, and all read-only transactions are concurrent with all writes. Consider the execution e_*:

S_1 : $r_{1,1}, \ldots, r_{N,1}, w_1$
S_2 : $w_2, r_{1,2}, \ldots, r_{N/M,2}$
S_3 : $w_3, r_{N/M+1,3}, \ldots, r_{2N/M,3}$
$\vdots$
S_{M+1} : $w_{M+1}, r_{N-N/M+1,M+1}, \ldots, r_{N,M+1}$
S_{M+2} : $w_{M+2}, r_{1,M+2}, \ldots, r_{N/M,M+1}$
$\vdots$
S_{M^2+1} : $w_{M^2+1}, r_{N-N/M+1,M^2+1}, \ldots, r_{N,M^2+1}$

By decomposing this execution into layers, we can inductively quantify the metadata required to process it. Let e_1 be the execution fragment containing all write requests and only

the read requests of R_1. Let e_i contain the requests of e_{i-1} plus all read requests of R_i, for $i = 2, \ldots, N$. Thus $e_N = e_*$.

Lemma 3. *Processing e_k while satisfying N+O+S requires $\Omega(kM^2)$ metadata, for $k = 1, \ldots, N$.*

Proof. The proof is by induction.

Base case. When $k = 1$, the only read requests in e_1 are those of R_1. By independent applications of Lemma 2, dependency $R_1 \rightarrow w_1$ must be transferred from S_1 to all $M-1$ servers targeted by R_1, i.e., all other S_j that receive $r_{1,j} \in R_1$. By the implication of Lemma 2, $R_1 \rightarrow w_1$ can be transferred through (1) a priori metadata in $r_{1,j}$ or (2) a posteriori metadata in the write protocol. For (2), observe that all write requests are issued concurrently with R_1, and w_1 is the only write processed after a read request $r_{1,1} \in R_1$. If $r_{1,1}$ contains no metadata, then the write protocol must (conservatively) transfer $R_1 \rightarrow w_1$ to every S_j, $j = 2, \ldots, M^2+1$. This requires $\Omega(M^2)$ metadata for these M^2 servers.

Alternatively, $r_{1,1}$ could convey the list of M servers targeted by R_1—this is a priori metadata—so that the write protocol need only send $R_1 \rightarrow w_1$ to the servers targeted by R_1 (as required by Lemma 2). However, consider the execution e'_1 that swaps the special role of S_1 with a different server S_j targeted by R_1. That is, S_j becomes the server that receives N read requests followed by a write, w_j. Such an execution is possible due to the asynchrony of the network (assumption A-2). In e'_1, w_j becomes the only write processed after a read request $r_{1,j} \in R_1$, so $r_{1,j}$ must convey the list of servers targeted by R_1. An analogous execution can be constructed for each server S_j targeted by R_1. Since it is not known a priori which execution will occur, and hence which $r_{1,j}$ will arrive before the write w_j, all $r_{1,j}$ must include the list of M servers. This requires $\Omega(M * M) = \Omega(M^2)$ metadata.

Inductive step. Assume the lemma holds for e_{k-1}; we show it also holds for e_k, which extends e_{k-1} with all read requests in R_k. By Lemma 2, dependency $R_k \rightarrow w_1$ must be transferred from S_1 to all $M-1$ servers targeted by R_k, i.e., all other S_j that receive $r_{k,j} \in R_k$. We show that this requires additional metadata beyond that of e_{k-1}. Consider the execution e'_k where all read requests in S_1 appear *after* w_1, except for $r_{k,1}$. Since $r_{k,1}$ is the only message that precedes w_1, it must either convey the list of M servers targeted by R_k, or the write protocol must send $R_k \rightarrow w_1$ to all servers. By the argument above, both methods require $\Omega(M^2)$ metadata. Thus e_k requires $\Omega((k-1)M^2) + \Omega(M^2) = \Omega(kM^2)$ metadata. ■

Completion of the proof. By Lemma 3, $e_* = e_N$ requires $\Omega(NM^2)$ metadata. Since $R_1, \ldots, R_N$ issue NM read requests total, the amortized metadata required per read request is $\Omega(\frac{NM^2}{NM}) = \Omega(M)$, which is not constant, violating C. ■

Extension to partial synchrony. A partially synchronous network [17] assumes that each machine has a physical clock that is approximately synchronized via some synchronization protocol, e.g., NTP [42] or Google's TrueTime [11], so that messages have bounded delays. Our NOCS Theorem still holds if the network is partially synchronous.

Under partial synchrony, Lemma 1 holds because the construction of e'_1 remains valid: the network can still deliver the response of w_2 faster than some time t, such that t is within the message delay bound, which results in $w_2 \rightarrow R$ in real-time. Lemma 2 holds because the origin of dependency $R \rightarrow w_1$ and the need to transfer it are independent of network models. Similarly, the main proof of the NOCS Theorem also holds because its construction, e_*, relies on concurrent read and write operations which are valid in either network model. Lemma 3 holds because the executions it constructs are rearrangements of e_* allowed by concurrency, and its method of calculating the size of metadata is independent of network models. Because all components of the proof hold under a partially synchronous network, the NOCS Theorem holds under partial synchrony.

B Proof of Correctness for PORT

We prove the correctness of PORT by proving that PORT is performance-optimal and process-ordered serializable.

B.1 Performance Optimality

PORT's read-only transactions are performance-optimal, i.e., they have the N, O, and C properties. They complete in a single round because clients specify the versionstamp to read at, which represents a consistent view across servers. They have no off-path messages. They avoid blocking for requested versions to be ready by promoting existing versions. They use only a constant amount of metadata, i.e., one integer (versionstamp) for a server to process a read.

B.2 Process-Ordered Serializability

According to the definition of process-ordered serializability (§6), we prove that for any execution of PORT, there exists a legal total order of requests, i.e., read-only transactions and write operations, such that the total order respects the process order of each client. More specifically, an algorithm π is process-ordered serializable if and only if there exists a total order in any execution of π, such that the total order satisfies the following requirements:

P. If x, y are requests from the same client, and x happened before y, then x appears before y in the total order.

Proof. For any execution of PORT, we construct a total order of requests as follows. Let $\mathbb{O}_1$ be a total order of all committed write operations where all writes are ordered by their versionstamps, and then writes with the same versionstamp are ordered lexicographically. Add omitted writes to $\mathbb{O}_1$ to get $\mathbb{O}_2$, where omitted writes are placed right before the concurrent write operation that elided them. For the omitted writes elided by the same concurrent write, we order them by their

versionstamps, and then lexicographically for the ones with the same versionstamp. Name the new order $\mathbb{O}_3$. Add read-only transactions to $\mathbb{O}_3$ by placing each read-only transaction directly after the last committed write with the same versionstamp, and name it $\mathbb{O}_4$. Now, order the read-only transactions with the same versionstamp from the same client by the order in which they were issued; order other read-only transactions with the same versionstamp arbitrarily, e.g., by client identifier; and name the final order $\mathbb{O}$.

$\mathbb{O}$ is legal because each read-only transaction request returns the value of a preceding write, i.e., at an earlier position in the order with no larger versionstamp. $\mathbb{O}$ is total because it includes all requests in the system, e.g., committed writes, omitted writes, and read-only transactions. $\mathbb{O}$ respects the process order of each client, i.e., satisfies P. More specifically, let x and y be arbitrary requests by the same client, and x happened before y without loss of generality. Because y happens later, $t_x \leq t_y$, where t_x and t_y are versionstamps, because versionstamps advance monotonically.

Case 1: $t_x < t_y$, then x appears before y in $\mathbb{O}$ due to the versionstamp order.

Case 2: $t_x = t_y$, then y cannot be a write because version clocks always tick on writes. If x is a write, then x appears before y in $\mathbb{O}$ by the construction of $\mathbb{O}_4$. If both x and y are read-only transactions, then x appears before y due to the final step of the construction of $\mathbb{O}$, i.e., the issuing order that x happened before y by the same client. Therefore, x is guaranteed to appear before y in $\mathbb{O}$.

The existence of a total order $\mathbb{O}$ proves that PORT is process-ordered serializable. ■

B.3 Note on Write Omission

In §6.3, we state that PORT can omit an incoming write if its versionstamp, vs_{omit}, is less than or equal to the highest committed versionstamp of the data item, $vs_{highest}$. This argument relies on the fact that a write with versionstamp $vs_{highest}$ cannot happen-before the omitted write since $vs_{highest} \geq vs_{omit}$. We justify this claim here.

Version clocks guarantee that if write x happens-before write y, then $vs_x < vs_y$. If they are from the same client then this is ensured by version clocks always ticking on writes. If they are from different clients, then for x to happen-before y there must be a chain of reads (of the previous write in the chain) and writes (by the same client as the previous read in the chain) connecting x and y. Because version clocks only advance, reads only observe writes with versionstamps less than or equal to their own, and each write in the chain ticks its clock, this chain ensures that $vs_x < vs_y$.

C Proof of Correctness for Eiger-PORT

Read-only transactions in Eiger-PORT always finish with one-round communication between client and server and do not require any off-path messages. They never block since reads always return an existing version. They use a constant amount of metadata, e.g., a server needs only one read timestamp to find the version for a read request. Therefore, Eiger-PORT is performance-optimal (N+O+C).

Now, we show the correctness of Eiger-PORT by proving that it is causally consistent and respects write isolation. Causality (happened-before relation), denoted by $\rightarrow$, has three requirements [3, 31]:

C_1. If x and y are requests by the same client (process), then $x \rightarrow y$ if the client did x before y.

C_2. If x is a write request and y is a read request that returns the value written by x, then $x \rightarrow y$.

C_3. For requests x, y, and z, if $x \rightarrow y$ and $y \rightarrow z$, then $x \rightarrow z$.

Write isolation, i.e., atomicity on writes [22, 23, 25], requires that either all updates in a write transaction are potentially visible to a read-only transaction or none of them are. The write transaction cannot be observed (read) to be in progress by another client. For instance, let $W = \{A = new, B = new\}$ be a write transaction that updates server A and B from "old" values to "new" values; let $R = \{A, B\}$ be a read-only transaction that reads server A and B. To respect write isolation, it is legal for R to return either $\{A = old, B = old\}$ or $\{A = new, B = new\}$. It would violate write isolation if R returns $\{A = old, B = new\}$ or $\{A = new, B = old\}$. The following requirement captures write isolation:

I_W. An algorithm, π, respects write isolation if and only if for any read-only transaction R and write transaction W, all read requests in R observe a system state either before or after applying all write requests in W.

We prove that any execution of Eiger-PORT satisfies C_1, C_2, C_3, and I_W. Our proof considers simple read/write operations as single-key transactions, and assumes each client has at most one outstanding request at any time.

Lemma 4. *Let w_1, w_2 be write requests, and t_{w1}, t_{w2} be their commit timestamps. If $w_1 \rightarrow w_2$, then $t_{w1} < t_{w2}$.*

Proof. This lemma directly follows the fact that Eiger-PORT is built on Eiger, a causally consistent system. More specifically, Eiger runs Lamport clocks, and commits each write request with a Lamport timestamp. Lamport clocks guarantee that if two requests $x \rightarrow y$, then x's Lamport timestamp is less than y's Lamport timestamp. ■

Lemma 5. *For any global safe time (gst), there do not exist ongoing write transactions with pending_time less than gst.*

Proof. Suppose there exists an ongoing write transaction W at global safe time gst and W arrives at an arbitrary server S at time t, such that $t < gst$. That is, $t_p < gst$, where t_p is W's *pending_time* on S. Given that the global safe time is the minimum local safe time across all servers, $gst \leq lst$, where lst is the local safe time on S at the time gst is computed.

Since $t_p < gst$ by our assumption and $gst \leq lst$, $t_p < lst$, which contradicts the fact that the local safe time is the minimum *pending_time* of all ongoing write transactions on the server, i.e., $lst \leq t_p$. Therefore, our initial assumption is invalid, and thus the original lemma is true. ■

Lemma 6. *If a read-only transaction reads at the stable frontier, then it returns the system state that includes the write transaction, which wrote the returned values, and all earlier write transactions the returned values depend on.*

Proof. Let R be a read-only transaction and gst be its read timestamp. R reads before the stable frontier. That is, R does not read any keys the client has recently written with commit time greater than gst. Let v be an arbitrary value returned by R, and W be the write transaction that wrote v. Let t_c be W's commit time. Since R returns v, R observes the effect of W. Let W' be an arbitrary write transaction, such that $W' \rightarrow W$. By Lemma 4, $t'_c < t_c$, where t'_c is the commit time of W'. Therefore, R returns v at a timestamp greater than the commit time of all write transactions W depends on. Given that read-only transactions read the system states in a monotonically increasing manner, i.e., the read timestamps (gst) increase monotonically, the read-only transaction R returns the system state after the system has applied W and all W's dependent writes. That is, R observes the effect of W and all earlier writes that W depends on. ■

Lemma 7. *If a read-only transaction reads beyond the stable frontier, then it returns the value of the most recent write transaction by the same client.*

Proof. Let R be a read-only transaction, which returns value v written by write transaction W. Let t_c be W's commit time and gst be R's read timestamp. This lemma directly follows the algorithm (Figure 8 lines 7—9) since Eiger-PORT reads beyond the stable frontier if and only if the same client has a recent write transaction that committed with a timestamp greater than the read timestamp, i.e., $t_c > gst$, where R returns the client's own most recent write. ■

Lemma 8 (C_1)**.** *Any execution of Eiger-PORT preserves the causal order required by C_1.*

Proof. Let c be an arbitrary client and x, y be its requests. Without loss of generality, x happened before y, i.e., c receives x's response and then issues y.

Case 1: x and y are both write transactions, then the way Eiger-PORT executes x and y satisfies C_1 by Lemma 4.

Case 2: x is a write transaction and y is a read-only transaction. Let gst be the timestamp y reads at, and t_c be x's commit time. If $gst \geq t_c$, then C_1 is satisfied by Lemma 6 since y returns a value, v, at a Lamport timestamp that includes x and all earlier writes x depends on. If $gst < t_c$ and x, y have common keys, then y reads beyond the stable frontier. By Lemma 7, y returns the values by the client's most recent write, which is x, and thus satisfies C_1. If $gst < t_c$ and x, y have disjoint sets of keys, then C_1 is satisfied by the fact that gst increases monotonically. More specifically, it is guaranteed that $gst \geq t_g$ where t_g is the global safe time when x was issued. That is, y is guaranteed to read a state no older than the system state y depends on.

Case 3: x is a read-only transaction and y is a write transaction. Let gst be x's read timestamp. Since $gst \leq lst \leq t_s$, where lst and t_s are the local safe time and current Lamport time respectively on the (arbitrary) server when x arrives at, then $x \leq t_s$. Because y is issued after x finishes, and the value of a Lamport clock increases monotonically, $t_s < t_c$, where t_c is the commit time of y. Therefore, $gst < t_c$.

Case 4: x and y are both read-only transactions. Let gst_x and gst_y be the read timestamps of x and y respectively. Because gst is advanced monotonically, $gst_x \leq gst_y$. That is, y observes all the updates x has observed. More specifically, the writes that have been applied by the system by the time gst_y is a super set of the applied writes by the time gst_x.

By the above four cases, the lemma is true. ■

Lemma 9 (C_2)**.** *Any execution of Eiger-PORT preserves the causal order required by C_2.*

Proof. Let W be a write transaction and R be a read-only transaction, such that R returns the value written by W. Let t_c be W's commit time, and gst be R's read timestamp. Similar to Case 2 in Lemma 8, if $gst \geq t_c$, then by Lemma 6, R observes the effect of W and all the write transactions W depends on. If $gst < t_c$, then R reads beyond the stable frontier and returns what W wrote, which implies that R and W are by the same client and access the same keys. Then the claim is true by Lemma 7. ■

Lemma 10 (C_3)**.** *Any execution of Eiger-PORT preserves the causal order required by C_3.*

Proof. This lemma directly follows the fact that the read timestamps, gst, and the values of Lamport clocks (for commit times of write transactions) are monotonically increasing. More specifically, let x, y, and z be three transactions and $x \rightarrow y$ and $y \rightarrow z$. Consider the following cases.

Case 1: y and z are write transactions, then x, y, and z are from the same client, and thus $x \rightarrow z$ is ensured by applying Lemma 8 on $x \rightarrow y$ and then on $y \rightarrow z$.

Case 2: y and z are read-only transactions, then it implies that y and z are from the same client, and thus $x \rightarrow z$ is guaranteed by applying either Case 4 of Lemma 8 or Lemma 9 on $x \rightarrow y$ depending on whether x is a read or a write, and then applying Case 4 of Lemma 8 on $y \rightarrow z$.

Case 3: y is a write transaction and z is a read-only transaction, then it implies that x and y are from the same client, and the order $x \rightarrow z$ is preserved by applying Lemma 8 on $x \rightarrow y$, and then applying either Lemma 8 or Lemma 9 on $y \rightarrow z$ depending on whether y and z are from the same client.

Case 4: y is a read-only transaction and z is a write transaction, then y and z are from the same client, and the order $x \rightarrow z$ is guaranteed by applying either Lemma 8 or Lemma 9 on $x \rightarrow y$ depending on whether x is a read or a write, and then applying Lemma 8 on $y \rightarrow z$. ■

Lemma 11 (I_W)**.** *Any execution of Eiger-PORT respects write isolation,* I_W.

Proof. Let R be an arbitrary read-only transaction that returns value, v. Let W be the write transaction that wrote v.

Case 1: R reads at the stable frontier, i.e., $t_c < gst$, where t_c is W's commit time and gst is R's read timestamp, then W has committed by Lemma 5, i.e., all parts of W have finished and have the same commit time t_c by the write transaction protocol (Figure 9 line 41). Therefore, R reflects a system state after all parts of W are applied.

Case 2: R reads beyond the stable frontier, i.e., $t_c > gst$. By our algorithm, W and R are from the same client, and the client reads its own most recent write. Given that each client has at most one outstanding transaction at any time, W has finished by the time R was issued. Therefore, R also reflects a system state where all parts of W are applied. ■

Proof of Eiger-PORT. We have proven that Eiger-PORT provides causal consistency by Lemma 8, Lemma 9, and Lemma 10, and respects write isolation by Lemma 11. ■

D PORT-SEQ Design

This section presents PORT-SEQ, a novel design supporting read-only transactions that are non-blocking (N), one-round communication (O), and strictly serializable (S).

D.1 Design Insights

The design of PORT-SEQ is inspired by the NOCS Theorem. In particular, the proof of Lemma 2 implies that if read-only transactions satisfy N+O+S, then write messages must transfer metadata to ensure that concurrent read-only transactions are legally ordered with respect to any real-time dependencies between the writes. This intuition drove us to leverage a sequencer that totally orders the write operations.

D.2 PORT-SEQ Algorithm

Figure 12 shows the pseudocode of PORT-SEQ, which has two components: the write protocol that handles simple write operations and the read-only transaction algorithm that is non-blocking and one-round communication. The write protocol involves a standalone machine that serves as a sequencer that serializes write operations. PORT-SEQ implements Lamport clocks, i.e., each write operation is assigned a Lamport timestamp upon commit.

The client uniquely identifies each read-only transaction with a transaction identifier (line 3). The client sends the read requests in a read-only transaction in parallel to relevant servers that have the data together with the transaction id (lines 4, 5). When the server receives a read request,

```
1  Client Side
2  function read_only_txn(<keys>):
3    txn_id = generate_uuid()
4    for k in keys # in parallel
5      vals[k] = read_txn(k, txn_id)
6    return vals
7
8  function write(key, val):
9    # send the request to the sequencer
10   SEQ::handle_write(key, val)
11   return
12
13 Server Side
14 function read_txn(key, txn_id):
15   if txn_id in rotxn_tracker_local
16     time = rotxn_tracker_local[txn_id]
17     return val = read_at_time(key, time)
18   rotxn_tracker_local.append(txn_id,
19                     logical_time.now())
20   return read(key)
21
22 function write(key, val, rotxn_tracker):
23   write(key, val)
24   rotxn_tracker_tmp = rotxn_tracker_local
25   rotxn_tracker_local = rotxn_tracker
26   return rotxn_tracker_tmp
27
28 Write Sequencer (SEQ)
29 rotxn_tracker[][]
30 sync function handle_write(key, val):
31   # writes are serialized
32   id_time[][] = server::write(
33     key, val, rotxn_tracker)
34   for id in id_time
35     if rotxn_tracker[id] is null
36       rotxn_tracker.append(id, id_time[id])
37   return
```

Figure 12: Pseudocode for PORT-SEQ.

it checks with its local variable, *rotxn_tracker_local*, which stores the information on which read-only transaction should read at which local time. If the read-only transaction has a corresponding entry in *rotxn_tracker_local*, then it returns the value at the time specified in *rotxn_tracker_local* (lines 15—17), otherwise, it stores its id and time (lines 18, 19) and returns the value at the current time (line 20).

The client sends the write requests to the sequencer (line 10), which processes the writes one by one in sequential order, i.e., there is one and only one write being processed at any given time in the system. The sequencer maintains a local variable, *rotxn_tracker*, which tracks concurrent read-only transactions in the system. *rotxn_tracker* is a map of read-only transaction id to its read timestamp. The sequencer imbeds *rotxn_tracker* to the write request sent to the corresponding server (line 33). When the server receives a write operation, it updates the local storage (line 23), and replaces its *rotxn_tracker_local* with *rotxn_tracker* received from the sequencer. Note that *rotxn_tracker* has all the necessary information for processing future read-only transactions, and the current *rotxn_tracker_local* includes the read-only transactions that have been seen by the server but not by the sequencer, so the write response returns this information back to the sequencer to update its *rotxn_tracker* (lines 26, 34—36). Because finished reads will not be received by the same server again, it is safe to replace *rotxn_tracker_local* with

rotxn_tracker upon receiving a write (line 25).

The PORT-SEQ algorithm is not practical because write operations are serialized. Moreover, the size of the information kept by the sequencer increases linearly *w.r.t.* the number of concurrent read-only transactions, i.e., PORT-SEQ does not have the C property.

D.3 Correctness

The writes in PORT-SEQ are serialized, and thus the write operations themselves present a strictly serializable order. The read-only transactions respect real-time order because if a read-only transaction, R, is issued in real time after a write operation, w, then all the read requests in the transaction arrive at the servers after the write operation finishes. That is, the earliest read request, r, that first arrives at the server will not find its corresponding entry in *rotxn_tracker_local* at the server since it is the first arrived request of R, and thus it will return the value at the current time. Because R begins after w finishes, then the current time of r is for sure after the end time of w. Because r is the first arrived request, all other reads in R will return values at the logical time no earlier than that of r. Therefore, R returns at a logical time after w.

PORT-SEQ also satisfies the total order requirement of strict serializability, because all its read-only transactions respect the serial order of writes. For instance, for two write operations w_1 and w_2, where w_1 is processed by the sequencer before w_2, then there is an ordering constraint between those two writes, i.e., $w_1 \rightarrow w_2$. There are three possible outcomes for a read-only transaction concurrent with w_1 and w_2: not see either w_1 or w_2, sees w_1 but not w_2, or sees both w_1 and w_2. All these three cases respect the serial total order of $w_1 \rightarrow w_2$. PORT-SEQ's read-only transactions never end up seeing w_2 but not w_1, which would violate the total serial order $w_1 \rightarrow w_2$ because the read-only transaction will for sure find a corresponding entry of itself in *rotxn_tracker_local* when it arrives at the same server as w_2, and thus returns the value at the time consistent with w_1, which is before w_2. Because PORT-SEQ's read-only transactions guarantee a total order that respects the real-time order, they are strictly serializable (S). Because they always finish in one on-path round, do not incur off-path messages, and never block, they satisfy N+O.

E A Discussion on Recent Work

Recent work concurrent with our own presented a theorem that implies performance-optimal read-only transactions are impossible in causally consistent systems that support simple writes [14]. The apparent discrepancy between their results and ours is rooted in the underlying assumptions.

The recent work requires that a transaction cannot return an arbitrarily old value for a key it wants to read, even if the arbitrarily old value would satisfy causal consistency. This leads them to conclude that clients cannot specify the timestamp for a transaction (a technique our protocols rely on, in contrast). Although the logical connection between these two statements may not immediately be apparent from reading their paper, it becomes apparent if we consider a worst-case scenario where every read-only transaction is issued by a brand new (or inactive) user (client session) that has no prior communication or state from the servers. Given an asynchronous setting (where there is no bound on clock skew), such a user would need at least one round of messages to query what the recent values are on each server, in order to avoid reading an arbitrarily old value. (The user cannot simply "guess" a timestamp to read at because there is no bound on clock skew.) Only upon receiving these values can the user determine a non-arbitrary timestamp (snapshot) across all servers, and then the transaction reads the servers at this snapshot time. This is essentially the two-round protocol described in their work. Since this worst-case setting requires at least two rounds of communication with the servers, it is not performance optimal.

In contrast, our theorem assumes that multiple transactions can be issued by the same user (client session) and that multiple users (client sessions) can be co-located on the same client machine, so transactions can leverage the information stored on the client machine. This information is obtained by previous transactions either from the same session or from other co-located client sessions. This type of scenario is widely deployed in practice: end users typically interact with a web tier that proxies requests to a backend storage system; the web tier machines act as "clients" to the storage system. It is common for these machines to host client sessions that issue a series of transactions, and to co-locate multiple client sessions on the same machine. Therefore, storing and sharing auxiliary information between transactions is possible. This is why clients in our PORT protocols are able to read fresh data using only one round of messages. (Figure 4f in Section 7 shows PORT has minimal staleness.)

Alternatively, if we relax their assumption to a more practical one that allows bounded clock skew, then we believe performance optimal read-only transactions are possible even in the worst-case scenario considered by the recent work. This is because well-synchronized physical clocks, e.g., the ones that run NTP, can be used to order transactions and index data versions, allowing read-only transactions to complete in one round. For instance, a read-only transaction can use a timestamp no smaller than the current value of the client's physical clock (e.g., in Eiger-PORT we could use physical clocks for the versionstamps). This avoids the first round of messages they needed to query recent values, effectively replacing it with a "guess" that is guaranteed to not be arbitrarily stale (staleness is bounded by the clock skew). Well-synchronized physical clocks are commonly available in distributed storage systems.

We have confirmed the above explanation with the authors of the recent work.