Warranties for Faster Strong Consistency

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Abstract

We present a new mechanism, warranties, to enable building distributed systems with linearizable transactions. A warranty is a time-limited assertion about one or more distributed objects. These assertions generalize optimistic concurrency control, improving throughput because clients holding warranties need not communicate to verify the warranty's assertion. Updates that might cause an active warranty to become false are delayed until the warranty expires, trading write availability for read availability. For workloads biased toward reads, warranties improve scalability and system throughput. Warranties can be expressed using language-level computations, and they integrate harmoniously into the programming model as a form of memoization. Experiments with warranties on some nontrivial programs demonstrate that warranties enable high performance despite the simple programming model.

1 Introduction

Strong consistency remains important for many applications. Although the trend for many systems has been to abandon consistency in order to achieve greater scalability, strong consistency is critical when lives or money are at stake. Examples include systems for medical information, banking, payment processing, and the military.

But even if the stakes aren't so high, abandoning strong consistency can have negative consequences. Users of weak consistency systems are often left confused by applications that appear buggy. Moreover, weak consistency systems can significantly complicate the programming model for application developers who try to detect and repair inconsistencies at the application layer. Consistency failures at the bottom of a software stack can percolate up through the stack and affect higher layers in unpredictable ways, requiring defensive programming and extra program logic.

The need for strong consistency and a simple programming model has kept databases with ACID transactions in business. However, ACID transactions are often considered to have poor performance, especially in a distributed setting. In this work, we introduce a new mechanism, *warranties*, that significantly improves the performance of strongly consistent transactions, enabling them to scale better both with the number of application clients in the system and with the number of persistent storage nodes. Warranties help avoid the unfortunate choice between consistency and performance.

A warranty is a limited guarantee that some (potentially complex) assertion remains true regarding the state of a distributed system. The guarantee is limited in that it eventually expires. But during the term of the warranty, the application can safely use it to perform computation locally without communicating with the server that issued the warranty. Warranties are like leases [17] in that they are time-limited, but differ in that they make a logical assertion rather than conferring rights to objects.

Warranties are used to implement linearizable transactions as a generalization of optimistic concurrency control (OCC) [26], which permits clients to aggressively cache their working set across transactions. Warranties can express guarantees that objects are up to date. For OCC, these guarantees are useful because clients can use them to reduce or avoid communication with persistent stores. Warranties are particularly effective in the common case of high read contention, where many clients want to share the same popular—yet mutable—data.

More generally, warranties can contain an assertion that the results of a language-level computation has not changed. These *computation warranties* offer a form of distributed memoization, allowing clients to share cached computation in the manner often currently done using distributed caches such as `memcached`—but with strong consistency guarantees that are currently lacking.

Overall, warranties offer an efficient way to manage the tension between consistency and scalability, and are a promising mechanism for implementing future distributed applications.

The remainder of this paper is structured as follows. Section 3 presents the warranty abstraction in more detail, and discusses its connection to leases. Section 4 explains in more detail how optimistic transactions are implemented using warranties. The mechanisms needed for computation warranties are explored in Section 5. Our implementation using the Fabric distributed object system is described in Section 6. The evaluation in Section 7

shows that warranties significantly improve the performance of both representative benchmarks and a substantial real-world program. Related work is discussed more broadly in Section 8, and we conclude in Section 9.

2 Background and system model

We assume a distributed system in which each node serves one of two main roles: *client nodes* perform computations locally using persistent data from elsewhere, and *persistent storage nodes* (*stores*) store the persistent data. Client nodes obtain copies of persistent data from stores, perform computations, and send updates to the persistent data back to the stores. For example, the lower two tiers of the traditional three-tier web application match this description: application servers are the clients and database servers are the stores.

Our goal is a simple programming model for application programmers, offering strong consistency so they do not need to reason about inconsistent or out-of-date state. In particular, we want linearizability [20], so each committed transaction acts as though it executes atomically and in logical isolation from the rest of the system. Linearizability strengthens serializability [35, 6] to offer external consistency.

A partially successful attempt at such a programming model is the Java Persistence API (JPA) [10], which provides an object–relational mapping (ORM) that translates accesses to language-level objects into accesses to underlying database rows. JPA implementations such as Hibernate [22] and EclipseLink [13] are widely used to build web applications. However, we want to improve on both the consistency and performance of JPA.

We assume that the working set of both clients and stores fits in the node's memory. This assumption is reasonable for many applications, though not for large-scale data analytics applications, which are not targeted by this work.

In a distributed transaction system using OCC (e.g., Thor [31]) clients fetch and then cache persistent objects across transactions. This optimistic caching means client transactions can largely avoid talking to stores until commit time, unlike with pessimistic locking. In effect, persistent data is replicated at the memories of potentially many client nodes; replication makes the system faster but means the cached copies can become inconsistent.

Because of its performance advantages, optimism has become increasingly popular for JPA applications, where the best performance is usually achieved through an "optimistic locking" mode that appears to provide strong consistency in some but not all implementations of JPA.[1]

[1]The term "optimistic locking" is misleading; locking occurs only during transaction commit. The JPA 2 specification appears to guarantee that objects *written* by a transaction are up to date—but, unfortunately, not the objects *read*. Implementations differ in interpretation.

To provide strong consistency, reads and writes to objects are logged to a transaction log. As part of committing the transaction, clients send the transaction log to stores involved in the transaction. The stores then check that the state of each object read matches that in the store (typically by checking version numbers), and then perform updates.

To scale up a distributed computing system of this sort, it is important to be able to add storage nodes to serve client requests, and to distribute the persistent data used by clients across these stores. As long as a given client transaction accesses data at just one store, and load is balanced across the stores, the system scales easily: each transaction can be committed with just one round trip between the client and the accessed store.

In general, however, a transaction accesses information located at multiple stores. For example, consider a web shopping application. A transaction that updates the user's shopping cart may still need to read information shared among many users of the system, such as details of the item purchased.

Accessing multiple stores hurts scalability. To commit such a transaction serializably, it must be known at commit time that all objects read during the transaction were up to date. A two-phase commit (2PC) is used. In the first phase (the prepare phase), each store both checks that the transaction can be committed and if so, readies the updates to be committed; it then reports to the coordinator whether the transaction is serializable. If the transaction can be committed at every store, all stores are told to commit in the commit phase. Otherwise, the transaction is aborted and its effects are rolled back.

If popular, persistent data is accessed by many clients, the read contention between clients interferes with scalability. Each client committing a transaction must execute a prepare phase at the store of that data. The work done by the prepare phase consists of *write prepares* done on objects that have been updated by the transaction, and *read prepares* on objects that have been read. In both cases, the object is checked to ensure that the version used was up to date.

Because of read prepares, nodes storing popular objects can become bottlenecks even when those objects are rarely updated. This is a fundamental limit on scalability of OCC, and a key benefit of warranties is addressing this performance bottleneck. An alternative strategy would be to replicate popular objects across multiple nodes, but keeping replicas in agreement is very costly.

3 The warranty abstraction

A warranty is a time-limited assertion about the state of the system: it is guaranteed to remain true for some fixed period of time. Warranties improve scalability for two reasons: first, because they reduce or eliminate the work

needed at read prepares; second, more generally, they make possible the distributed caching of computations.

Because warranties make guarantees about the state of the system, they allow transactions to be committed without preparing reads against the objects covered by warranties. When all reads to a store involved in a transaction are covered by warranties, that store need not be contacted. Consequently, two-phase commit can be reduced a one-phase commit in which the prepare and commit phases are consolidated, or even to a zero-phase commit in which no store need be contacted. The result is a significant improvement to performance and scalability.

In this section, we give a more detailed overview of how warranties work.

- Simple *state warranties* generalize OCC (§3.1) and also, to some extent, leases (§3.2).
- Updates to the system are prevented from invalidating warranties (§3.3), with implications for performance (§3.4).
- Warranty assertions can be expressive, enabling distributed caching of computed results (§3.5).
- Warranties are requested by clients (§3.6) and generated on demand by stores (§3.7).
- Warranties are distributed throughout the system to clients that need them (§3.8).
- The term of warranties can be set automatically, based on run-time measurements (§3.9).

3.1 State warranties

The simplest form of warranty is a *state warranty*, an assertion that the concrete state of an object has a particular value. State warranties generalize optimistic concurrency control in a simple way. A client that queries a store to obtain the state of an object receives, in addition to the object's current state, a guarantee that the state will not change for some period of time.

A warranty is guaranteed to be true (*active*) during the warranty's *term*. At the end of its term, the warranty *expires* and is no longer guaranteed to be true.

For example, a state warranty for an object representing a bank account might be ⟨`assert = {name = "John Doe", bal = $20,345}, exp = 1364412767.1`⟩. Here, the field `assert` specifies the state of the object, and the field `exp` is the time that the warranty expires.

A warranty is issued by a store, and times appearing in the warranties are measured by the clock of the store that issued the warranty. We assume that clocks at nodes are loosely synchronized; well-known methods exist to accomplish this [34].

If a warranty expires before the transaction commits, the warranty may continue to be *valid*, meaning that the assertion it contains is still true even though clients cannot rely on its remaining true. Clients can, however, still use the warranty optimistically and check at commit time that the warranty remains valid. Use of expired warranties is simply OCC, and ordinary OCC can be viewed as the use of warranties that immediately expire.

3.2 Warranties vs. leases

Warranties are related to leases [17], which are time-limited locks on objects that grant certain rights over those objects. Leases have been used in many systems (e.g., [43]) to increase scalability by reducing coordination between nodes. Leases may be shared by multiple clients but must be held to perform the operations they govern. They do not target transactional systems.

Unlike leases, warranties are time-limited *assertions* about what is *true* in the distributed system. They are not, therefore, held by any particular set of nodes in the system. Unlike leases, warranties permit nodes to attempt to update objects even when the client has no warranty for the object. However, the assertions made by warranties must consequently be *defended* against updates that might invalidate them. As discussed later, warranties also differ from leases in that warranties may depend on other warranties, because they are assertions about computations that may use other warranties.

3.3 Defending warranties

Transactions may try to perform updates that affect objects on which active warranties have been issued. Updates cannot invalidate active warranties without potentially violating transactional isolation for clients using those warranties. Therefore, stores must defend warranties against invalidating updates, a process that has no analogue in OCC.

A warranty can be defended against an invalidating update transaction in two ways: the transaction can either be rejected or delayed. If rejected, the transaction will abort and the client must retry it. If delayed, the updating transaction waits until it can be safely serialized. Rejecting the transaction does not solve the underlying problem of warranty invalidation, so delaying is typically the better strategy if the goal is to commit the update. To prevent write starvation, the store stops issuing new warranties until after the commit. The update also shortens the term of subsequent warranties.

3.4 Performance tradeoffs

Using warranties improves read performance for objects on which warranties are issued, but delays writes to these objects. Such a tradeoff appears to be an unavoidable outcome of enforcing strong consistency. For example, in conventional database systems that use pessimistic locking to enforce consistency, readers are guaranteed

to observe consistent states but update transactions must wait until all read transactions have completed and released their locks. With many simultaneous readers, the delay for writers can be substantial. Thus, warranties occupy a middle ground between optimism and pessimism, using time as a way to reduce the coordination overhead incurred with locking.

The key to good performance, then, is to issue warranties that are long enough to allow readers to avoid revalidation but not so long that they block writers more than they otherwise would be blocked.

For applications where it is crucial to have both high write throughput and high read throughput to the same object, replication is essential, and the cost of keeping object replicas in sync makes strong consistency infeasible. However, if weak consistency is acceptable, there is a simple workaround: implement replication by explicitly maintaining the state in multiple objects. Writes can go to one or more persistent objects that are read infrequently, and only by a process that periodically copies them (possibly after reconciliation of divergent states) to a frequently read object on which warranties can be issued. This is a much easier programming task than starting from weak consistency and trying to implement strong consistency where it is needed. The only challenging part is reconciliation of divergent replicas, which is typically needed in weakly consistent systems in any case (e.g., [42, 39, 12]).

3.5 Computation warranties

Warranty assertions are not limited to specifying the concrete state of persistent objects. In general, a warranty assertion is an expression in a language that can describe a computation that operates on persistent objects and that can be evaluated at the store. SQL is one query language that fits this description. In this work, we integrate assertions more tightly with the programming language. Computation warranties provide guarantees about computations described in terms of method calls.

In current distributed applications, it is common to use a distributed cache such as `memcached` [15] to share data and computation across many nodes. For example, web application servers can cache the text of commonly used web pages or content to be included in web pages. Computation warranties can be used to cache such computed results without abandoning strong consistency.

Example: top N items. Many web applications display the top-ranked N items among some large set (such as advertisements, product choices, search results, poll candidates, or game ladder rankings).

Although the importance of having consistent rankings may vary across applications, there are at least some cases in which the right ranking is important and may have monetary or social impact. Election outcomes matter, product rankings can have a large impact on how money is spent, and game players care about ladder rankings. But at present there is no easy and efficient way to ensure that cached computation results are up to date.

To cache the results of such a computation, we might define a computation `top(n, i, j)`, which returns the set `s` of the `n` top-ranked items whose indices in an array of items lie between `i` and `j`. A warranty of the form `s = top(n, 0, num_items)` then allows clients to share the computation of the top-ranked items within the range.

The reason why the `top` function has arguments `i` and `j` is to permit `top` to be implemented recursively and efficiently using results from subranges, on which further warranties are issued. We discuss later in more detail how this approach allows computation warranties to be updated and recomputed efficiently.

Example: airplane seats. Checking whether airplane flights have open seats offers a second example of a computation that can be worth caching. Because the client-side viewer may be sorting lists of perhaps hundreds of potential flights, flights are viewed much more often than their seating is updated. Scalability of the system would be hurt by read prepares.

Efficient searching over suitable flights can be supported by issuing warranties guaranteeing that at least a certain number of seats of a specified type are available; for a suitable constant number of seats n large enough to make the purchase, a warranty of this form works:

$$\texttt{flight.seats\_available(type)} \geq n$$

This warranty helps searching efficiently over the set of flights on which a ticket might be purchased. It does not help with the actual update when a ticket is purchased on a flight. In this case, it becomes necessary to find and update the actual number of seats available. However, this update can be done quickly as long as the update does not invalidate the warranty.

Like state warranties, computation warranties can be used optimistically even if they expire during the transaction. In this case, the dependencies of the computation described in the warranty must be checked at commit time to ensure that the warranty's assertion remains true, just as objects whose state warranties expire before commit time must be checked. A warranty that is revalidated in this fashion can then be issued as a new warranty.

Like active state warranties, active computation warranties must be defended against invalidation by updates. This mechanism is discussed in Section 5.2.

3.6 Programming with warranties

As clients compute, they request warranties as needed. State warranties are requested automatically when ob-

jects are newly fetched by a computation. Computation warranties can also be generated in a natural way, relying on simple program annotations.

Computation warranties explicitly take the form of logical assertions, so they could be requested by using a template for the desired logical assertion. In the airline seat reservation example above, a query of the form `flight.seats_available(type)` $\geq ?$ could be used to find all available warranties matching the query, and at the same time fill in the "?" with the actual value n found in the warranty.

A simple and transparent way to integrate warranty queries into the language is via memoized function calls. For example, we can define a memoized method with the signature `memoized boolean seats_lb(type,` n`)` that returns whether there are at least n seats of the desired type still available on the flight. The keyword `memoized` indicates that its result is to be memoized and warranties are to be issued on its result. To use these warranties, client code uses the memoized method as if it were an ordinary method, as in the following code:

```
for (Flight f : flights)
  if (f.seats_lb(aisle, seats_needed))
    display_flights.add(f)
```

When client code performs a call to a memoized method, the client automatically checks to see if a warranty for the assertion $? =$ `seats_lb(type, n)` has either been received already or can be obtained. If so, the result of the method call is taken directly from the warranty. If no warranty can be found for the method call, the client executes the method directly.

With appropriate language support, the implementation of such a memoized method is also straightforward:

```
memoized boolean seats_lb(Seat t, int n) {
    return seats_available(t) >= n;
}
```

A language that correctly supports transparent OCC already automatically logs the reads and writes performed on objects; this logging already computes the dependencies of computation warranties.

3.7 Generating warranties

Warranties are issued by stores, because stores must know about warranties in order to defend them against updates that might invalidate them. However, for scalability, it is important to avoid giving the store extra load. Therefore, it only makes sense to generate warranties for some objects and computations: those that are used much more frequently than they are invalidated.

For state warranties, the store already has enough information to decide when to generate a warranty for an object, because it sees both when the object is updated and when it is necessary to check that the version of the object read by a client is up to date. State warranties improve performance by removing the need to do version checks on read objects, but at the cost of delaying updates that would invalidate active warranties. This tradeoff makes sense if the version checks are sufficiently more numerous than the updates.

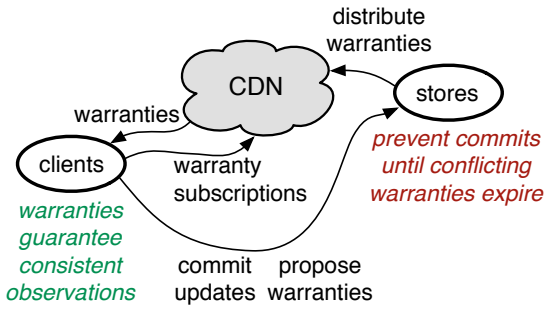


Figure 1: Warranty distribution architecture.

For computation warranties, the store may be able to infer what warranties are needed from client requests, but it makes more sense to have the client do the computational work. Recall that clients that fail to find a suitable warranty compute the warranty assertion themselves. If the assertion is true, it is the basis of a potential warranty that is stored in the client's local cache and reused as needed during the same transaction. As part of committing the transaction, the client sends such potential warranties to the store, which may issue these warranties, both back to this client and to other clients. The decision whether to issue a warranty properly depends on whether issuing the warranty is expected to be profitable.

3.8 Distributing warranties

Warranties can be used regardless of how they get to clients and can be shared among any number of clients. Therefore, a variety of mechanisms can be used to distribute warranties to clients.

One option for warranty distribution is to have clients directly query stores for warranties, but this makes the system less scalable by increasing load on stores. As shown in Figure 1, Stores will be less loaded if warranties are distributed via a content distribution network (CDN) that clients query to find warranties.

Going a step further, applications can *subscribe* to warranties that match a given pattern, as shown in Figure 1. Stores automatically *refresh* warranties with later expiration times before the old warranties expire, by pushing these extended warranties either directly to clients or into the CDN. Warranty refresh makes it feasible to satisfy client requests with shorter warranty terms, consequently reducing write latency.

This strategy for achieving high availability and high

durability differs from that used in many current distributed storage systems, which use replication to achieve high availability, low latency, and durability. Those three goals are handled separately here. Distributing warranties through a CDN makes data objects highly available with low latency, without damaging consistency. Because the authoritative copies of objects are located at stores, a write to an object requires a round-trip to its store; the latency this introduces is ameliorated by the support for relatively large transactions, in which communication with stores tends to happen at the end of transactions rather than throughout.

To achieve high durability, stores should be implemented using replication, so that each "store" mentioned in this paper is actually a set of replicas. Since wide-area replication of stores implementing strong consistency will have poor performance, we assume store replicas are connected with low latency.

3.9 Setting warranty terms

Depending on how warranty terms are set, warranties can either improve or hurt performance. However, it is usually possible to automatically and adaptively set warranty terms to achieve a performance increase.

Warranties improve performance by avoiding read prepares for objects, reducing the load on stores and on the network. If *all* read and write prepares to a particular store can be avoided, warranties eliminate the need even to coordinate with that store.

Warranties can hurt performance primarily by delaying writes to objects. The longer a warranty term is, the longer the write is delayed. If warranty terms are set too long, writers may experience unacceptable delays. A good rule of thumb is that we would like writers to be delayed no more than they would be by read locks in a system using pessimistic locks.

Excessively long warranties may also allow readers to starve writers, although starvation is mitigated because new warranties are not issued while writers are blocked waiting for a warranty to expire. Note that with pure OCC, writers can block readers by causing all read prepares to fail [36]; thus, warranties shift the balance of power away from writers and toward readers, addressing a fundamental problem with OCC.

To find the right balance between the good and bad effects of warranties, we take a dynamic, adaptive approach. Object warranty terms are automatically and individually set by the system. Warranty terms are set by stores; fortunately, stores observe enough to estimate whether warranty terms are likely to be profitable. Stores see both read prepares and write prepares. If the object receives many read prepares and few or no write prepares, a warranty is likely to be profitable.

To determine the warranty term L for a given object,

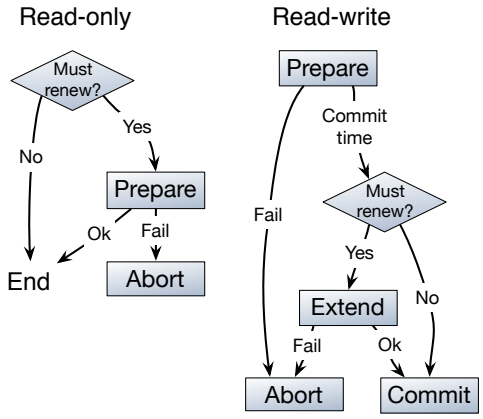


Figure 2: Warranty commit protocol for read-only and read-write transactions.

we use a simplified system model. Time spent between warranties is assumed to be negligible. At most one write is assumed to occur during a warranty period (if W is the rate of writes to the object, we have $LW \leq 1$). The prepare latency P is the time required to prepare and commit a transaction without the benefit of warranties, including all network delays. New warranties take time N to propagate to readers, so $\frac{N}{L}$ of all read-only transactions prepare to the store. If R is the rate of read prepares to the object, the store sees a read-prepare rate of $\rho = \frac{RN}{L}$ and average read latency is $\frac{PN}{L}$. On average, writes are delayed by $\frac{L}{2}$, so the average write latency is $P + \frac{L}{2}$. Therefore, the average transaction latency is $\frac{1}{R+W}\left(\frac{RPN}{L} + W(P + \frac{L}{2})\right)$. This term is minimized when $L = \frac{2\rho P}{W}$.

By monitoring client prepare requests, the store estimates the current values for ρ and W on each object. It then adjusts the target warranty term according to the formula above. Keeping track of the statistics does add per-object space overhead, but it pays off.

The formula for warranty terms improves throughput, but it can lead to long warranty terms on infrequently updated objects, and significant latency on updates when they do occur. The tension between write latency and read throughput can be eased by using warranty refresh. The warranty term L is computed as above, but warranties are issued a shorter term corresponding to the maximum acceptable update latency. The issuing store then proactively refreshes each warranty when it is about to expire, so that clients have a valid warranty throughout the warranty term. Clients needing warranty refreshes are identified via the subscription mechanism; refreshes can be distributed via the CDN.

This way to set terms for state warranties also works for computation warranties, with the following interpretation: uses of a computation warranty is a "read" and an

Stores	Stores written	Unexpired?	Phases: Warranties	Phases: OCC
1+	0	Y	0	1
1+	0	N	1	1
1	1	Y/N	1	1
2+	1	Y	1	2
2+	1	N	2	2
2+	2+	Y	2	2
2+	2+	N	3	2

Table 1: Warranties require fewer phases than traditional OCC in some cases (highlighted).

update to its dependencies is a "write".

4 Transactions and warranties

Warranties improve the performance of OCC by reducing the work needed during the prepare phase and by allowing phases to be eliminated entirely.

4.1 The warranty commit protocol

When a transaction is complete, the client performs a modified two-phase commit, which is illustrated in Figure 2 for both read-only and read-write transactions. In the prepare phase, the client sends the write set of the transaction (if any), along with any warranties in the read set whose term has expired. If all warranties in the read set can be renewed, the transaction may commit. However, since outstanding warranties may cause the updates to be delayed, the store responds with a *commit time* indicating when the commit may be applied successfully.

When the client has received a commit time from all stores, it checks to ensure the terms of the warranties it holds exceed the maximum commit time. If not, the client attempts to renew these warranties beyond the commit time in an additional *extend* phase. If active warranties are obtained for all dependencies, the client sends the commit message and the stores commit the updates at the specified time.

4.2 Avoiding protocol phases

While a two-phase commit is required in the general case, performance can be improved by eliminating or combining phases when possible. For read-only transactions, the commit phase is superfluous, and clients executing transactions that involve only one store can combine the prepare and commit phases into one round-trip. The optimizations to 2PC that warranties make possible are summarized in Table 1.

The read-only (rows 1–2) and single-store optimizations (row 3) are available with or without warranties. However, unexpired warranties enable eliminating additional phases, shown by the two rows highlighted in gray.

Row 1 shows that read-only transactions whose read set is covered by unexpired warranties may commit without communicating with stores—a zero-phase commit. This optimization matters because for read-biased workloads, most transactions will be read-only. On popular data that is rarely updated, longer warranties may be issued, making transactions more likely to have unexpired warranties at commit. Many or even most transactions can commit with no communication at all.

Row 4 shows that transactions that read from multiple stores but write to only one store may commit in a single phase if their read set is fully warrantied. This single-phase optimization pays off if objects are stored in such a way that writes are localized to a single store. For example, if a user's information is located on a single store, transactions that update only that information will be able to exploit this optimization.

While warranties usually help performance, they do not strictly reduce the number of phases required to commit a transaction. Transactions performing updates to popular data may have their commits delayed. Since the commit time may exceed the expiration time of warranties used in the transaction, the additional *extend* phase may be required to renew these warranties beyond the delayed commit time, as shown in the final row.

5 Computation warranties

A computation warranty is a guarantee until time t of the truth of a logical formula ϕ, where ϕ can mention computational results such as the results of method calls. We focus here on the special case of warranties generated by memoized function calls, where ϕ has the form $o.f(\vec{x}) =?$ for some object o on which method f is invoked using arguments $\vec{x}$, producing a value to be obtained from the warranty. Note that the value returned by f need not be a primitive value. In the general case, it may be a data structure built from both new objects constructed by the method call and preexisting objects.

Central to the goal of warranties is that they should not complicate programmers' reasoning about correctness or consistency. Therefore, when f is a memoized method, a computation of the form $v = o.f(\vec{x})$ occurring in a committed transaction should behave identically whether or not a warranty is used to obtain its value. This principle has several implications for how computation warranties work. It means that only some computations make sense as computation warranties, and that updates must be prevented from invalidating active warranties.

5.1 Memoizable computations

To ensure that using a computation warranty is equivalent to evaluating it directly, we impose three restrictions.

First, computation warranties must be deterministic: given equivalent initial state, they must compute equiv-

alent results. Therefore, computations using a source of nondeterminism, such as input devices or the system clock, do not generate computation warranties.

Second, we prevent memoization of any computation that has observable side effects. Side effects are considered to be observable only when they change the state of objects that existed before the beginning of the memoized computation.

Importantly, this definition of "observable" means that memoized computations are allowed to create and initialize new objects as long as they do not modify pre-existing ones. For example, the top-N example from Section 3.5 computes a new object representing a set of items, and it may be convenient to create the object by appending items sequentially to the new set. Warranties on this kind of side-effecting computation are permitted. Enforcing this definition of the absence of side effects is straightforward in a system that already logs which objects are read and written by transactions.

Third, a memoized function call reads from some set of objects, so updates to those objects may change its result, and may occur even during the same transaction that performed the function call. At commit time, the transaction's write set is intersected with the read set of each potential warranty. If the intersection is nonempty, the potential warranty is invalidated.

5.2 Defending computation warranties

Once a computation warranty is requested by a worker and issued by a store, the store must ensure that the value of the call stays unchanged until the warranty expires.

Revalidation A conservative way to defend warranties against updates would be to delay all transactions that update objects used by the warranty. This approach is clearly safe because of the determinism of the warranty computation, but it would prevent too many transactions from performing updates, hurting write availability. Instead, we attempt to *revalidate* affected warranties when each update arrives. The store reruns the warranty computation and checks whether the result is equivalent to the result stored in the warranty.

For primitive values and references to pre-existing objects (not created by the warranty computation), the result must be unchanged. Otherwise, two results are considered equivalent if they are semantically equal per the `equals()` method, which operates as in Java.

Warranty dependencies In general, a warranty computation uses and thus depends on other warranties, whether state warranties or general computation warranties. For example, if the method `top` is implemented recursively (see Figure 3), the warranty for a call to `top` depends on warranties for its recursive calls. The dependencies between warranties form a tree in which computation warranties higher in the tree depend on warranties lower down, and the leaves are state warranties.

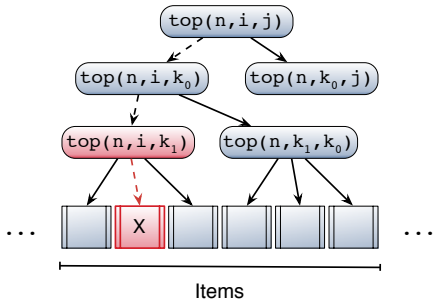


Figure 3: An update to X causes a semantic warranty to be invalidated, but the updated value for the re-evaluated method does not invalidate other warranties.

Any warranty that has not expired must be defended against updates that could invalidate it. Defense is easy when the term of a warranty is contained within (a subset of) the terms of all warranties it depends on, including state warranties on all direct references to objects, because the validity of the higher-level warranty is implied by the defense of the lower-level warranties.

In general, however, a warranty can have a longer term than some of its dependencies. Updates to those dependencies must be prevented if they invalidate the warranty, even if they are expired warranties. Conversely, it is possible to allow updates to warranty dependencies that do not invalidate the warranty. The implication is that it is often feasible to give higher-level warranties longer terms than one might expect given the rate of updates to their dependencies.

For example, consider the recursive call tree for the method `top(n, i, j)` shown in Figure 3. If the request to see the top n items among the entire set is very popular, we would like to issue relatively long computation warranties for that result. Fortunately, updates to items (shown at the leaves of the call tree) that change their ranking might invalidate some of the warranties in the tree, but most updates will affect only a small part of the tree. Assuming that lower levels of the tree have short warranties, most updates need not be delayed much.

5.3 Reusing computation warranty values

In the case where the warranty computation created new objects, it may be crucial for correctness of the computation that the objects returned by the warranty are distinct from any existing objects. This desired semantics is achieved when using a warranty computation result by making a copy of all objects newly created during the warranty computation. These objects are explicitly identified in the warranty.

Computation warranties are used whenever available to the client, to avoid performing the full computation. If the client is holding an expired warranty, or obtains an expired warranty from the CDN, it can use that expired warranty optimistically. At commit time, the expired warranty is revalidated during the prepare phase, exactly like a read prepare.

5.4 Creating computation warranties

Whenever code at a client makes a call to a memoized method, the client searches for a matching computation warranty. If the client is not already holding such warranty, it may search using a CDN, if available, or request the warranty directly from the appropriate store.

If the client cannot find an existing computation warranty, it performs the warranty computation itself. It starts a new transaction and executes the method call. As the call is evaluated, the transaction's log keeps track of all reads, writes, and object creations performed by the call. When the call is completed, the result is recorded and the log is checked to verify that the call does not violate any of the restrictions outlined above. If the warranty is still valid, the call, value, and transaction log are gathered to form a complete warranty proposal.

At commit time, if the warranty proposal has not already been invalidated by an update to its read set, the proposal is sent to the store. The store looks at the request and, using the same mechanism as for state warranties, sets a warranty term. Whereas for state warranties, terms are set individually for distinct objects, here the notion of identity is defined by the entire set of arguments to the memoized method. Finally, the computation warranty is issued to the requesting client and the store begins to defend the new warranty or warranties proposed by the client.

6 Implementation

To evaluate the warranty mechanism, we extended the Fabric secure distributed object system [32]. Fabric provides a high-level programming model that, like the Java Persistence API, presents persistent data to the programmer as language-level objects. Language-level objects may be both persistent and distributed. It implements linearizability using OCC.

Fabric also has many security-related features—notably, information flow control—designed to support secure distributed computation and also secure mobile code [3]. The dynamic security enforcement mechanisms of Fabric were not turned off for our evaluation, but they are not germane to this paper.

We extended the Fabric system and language to implement the mechanisms described in this paper. Our extended version of Fabric supports both state warranties and computation warranties. Computation warranties were supported by extending the Fabric language with memoized methods. Client (worker) nodes were extended to use warranties during computation and to evaluate and request computation warranties as needed. The Fabric dissemination layer, a CDN, was extended to distribute warranties and to support warranty subscriptions. Fabric workers and stores were extended to implement the new transaction commit protocols, and stores were extended to defend and revalidate warranties.

The previously released version of Fabric (0.2.0) contains roughly 44,000 lines of (non-blank, non-comment) code, including the Fabric compiler and the run-time systems for worker node, store nodes, and dissemination nodes, written in either Java or the Fabric intermediate language. In total, about 6,600 lines of code were added or modified across these various system components to implement warranties.

Fabric ships objects from stores to worker nodes in object groups rather than as individual objects. State warranties are implemented by attaching individual warranties to each object in the group.

Some features of the warranties design have not been implemented; most of these features are expected to improve performance further. The single-store optimization of the commit protocol has been implemented for base Fabric but not for warranties. We expect this feature to significantly improve the performance and scalability seen with warranties, as it did with base Fabric. The warranty refresh mechanism is also not yet implemented. When implemented, this mechanism should add minimal load and significantly reduce write latency. Our implementation of transaction validation does not use timestamps to detect false conflicts; we expect this will increase throughput and reduce the abort rate.

To simplify the work needed to defend computation warranties, the current implementation only generates warranties for computations that involve objects from a single store. Also, our implementation does not use the dissemination layer to distribute computation warranties.

7 Evaluation

We evaluated warranties against existing OCC mechanisms, and other transactional mechanisms, primarily using three programs. First, we used the multiuser OO7 benchmark [11]. Second, we used versions of Cornell's deployed Course Management System [8] (CMS) to examine how warranties perform under real-world workloads. Both of these programs were ported to Fabric in prior work [32]. Third, we developed a new benchmark that simulates a component of a social network in which users have subscribers.

7.1 Multiuser OO7 benchmark

The OO7 benchmark was originally designed to model a range of applications typically run using object-oriented databases. The database consists of several modules, which are tree-based data structures in which each leaf of the tree contains a randomly connected graph of 20 objects. Each OO7 transaction performs 10 random traversals on either the *shared* module or a *private* module specific to each client. When the traversal reaches a leaf of the tree, it performs either a read or a write action. These are relatively heavyweight transactions compared to many current benchmarks; each transaction reads about 460 persistent objects and modifies up to 200 of them. By comparison, if implemented in a straightforward way with a key-value store, each transaction would perform hundreds of get and put operations. Transactions in the commonly used TPC-C benchmark are also roughly an order of magnitude smaller [44], and in the YCSB benchmarks [46], smaller still.

The ratios of shared to private and read to write traversals are configurable. For our evaluations we ran a workload consisting of 5.9% private reads, 0.1% private writes, 93.9% shared reads, and 0.1% shared writes. Since each transaction performs 10 traversals, this workload results in approximately 2% of transactions containing writes. We call this workload the *RW* workload.

Because OO7 transactions are relatively large, and because of the data's tree structure, OO7 stresses a database's ability to handle read and write contention. We increased read contention further by modeling the reality that shared data is not all equally popular. We modified the original OO7 benchmark so that the level of contention on popular shared objects increases with the number of users. We also modified traversals to make requests exhibit a typical power-law distribution with $\alpha = 0.7$ [9].

7.2 Course Management System

The CS Course Management System [8] (CMS) is a 54k-line Java web application used by the Cornell computer science department to manage course assignments and grading. The production version of the application uses a conventional SQL database, but when viewed through the JPA, the persistent data forms an object graph hierarchy not dissimilar to that of OO7. We modified this application to run on Fabric. To evaluate computational warranties, we designated several frequently-used access control methods as "memoized".

We obtained a trace from Cornell's production CMS server from three weeks in 2013, a period that encompassed multiple submission deadlines for several courses. As an indication of the read bias of this workload, the trace exhibits roughly a 40:1 GET/POST ratio.

To drive our performance evaluation, we took the 11 most common action types from the trace, transforming query parameters as necessary to map to objects in our test database. Each transaction in the trace is a complete user request including generation of an HTML web page, so some request types access many objects. Using JMeter [24] as a workload generator, we sampled the transformed trace. For actions that use a POST, we generated random POST data with a custom JMeter plugin.

7.3 Top-subscribers benchmark

The third benchmark program simulates a relatively expensive analytics component of a social network in which users have subscribers. The analytics component computes the set of 5 users with the largest number of subscribers, using the memoized top-N function described in Section 3.5. The number of subscribers per user is again determined by a power-law distribution with $\alpha = 0.7$. The workload consists of a mix of evaluations of two operations: 98% compute the list of top subscribers, corresponding to viewing the home page of the service; 2% are updates that randomly either subscribe or unsubscribe some randomly chosen user. This example explores the effectiveness of computational warranties for caching expensive computed results.

7.4 Comparing with EclipseLink/HSQL

To provide a credible baseline for performance comparisons, we also ported our implementations of OO7 and CMS to the Java Persistence API (JPA) [10]. We ran these implementations with the widely used EclipseLink implementation of JPA 2, running on top of HyperSQL, a popular in-memory database[2]. For JPA, we present results only for a single database instance. While JPA applications can interact with other frameworks to implement multi-database transactions, these frameworks are not available to standard JavaSE applications. Even in this single-store setting, and even with EclipseLink running in its optimistic locking mode, Fabric significantly outperforms EclipseLink in all of our experiments below. (Note that JPA in optimistic locking mode is in turn known to outperform JPA with pessimistic locking on read-biased workloads [41, 14]). This performance comparison is intended to show that Fabric is a good baseline for evaluating the performance of transactional workloads: it offers performance competitive with other persistent storage frameworks that offer a transactional language-level abstraction.

7.5 System model

Our experiments use a semi-open system model. An open system model is usually considered more realistic [40] and a more appropriate way to evaluate system

[2] We refer to EclipseLink/HSQL as *JPA* for brevity.

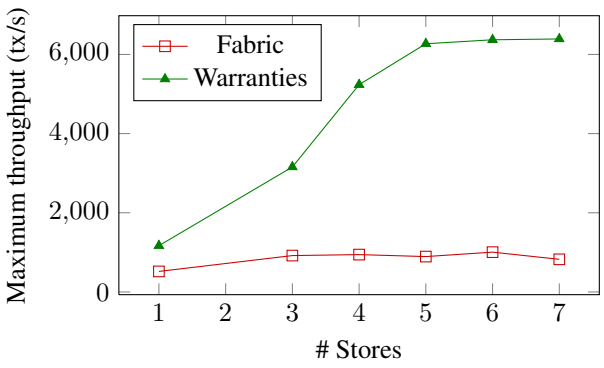


Figure 4: OO7 maximum throughput as the number of stores increases. Warranties allow Fabric throughput to scale up with more stores. Throughput for more than five stores is currently limited by ability to drive enough load.

scalability. In our model, worker nodes execute transactions at exponentially distributed intervals at a specified *average request rate*. Consequently, each worker is usually running many transactions in parallel. Overall system throughput is the sum of the throughputs at each worker. To find the maximum throughput, we increase the average request rate until the system cannot achieve the target throughput.

The experiments are run on a Eucalyptus cluster. Each store runs on a virtual machine with a dual core processor and 8GB of memory. Worker machines are virtual machines with 4 cores and 16GB of memory. The physical processors are 2.9GHz Intel Xeon E5-2690 processors.

7.6 Results

Scalability. We evaluated scalability using the OO7 benchmark with different numbers of stores. To preserve locality, a single store was reserved for the shared module, and the private modules were divided equally among the remaining stores. This scheme models a common scenario where popular data creates a bottleneck, limiting the benefit of balancing load across the private stores. Results presented are the average of three runs. Throughput targets not met by all three runs are omitted.

Figures 4 shows maximum throughput as the number of stores increases. As expected, the increase in stores has little effect on maximum throughput in base Fabric since the bottleneck at the shared store remains. With warranties, load on the shared store is greatly reduced. Over the range of throughput that we were able to drive with 15 quad-core worker nodes, we could add roughly 1,000 transactions/sec per additional store.

Latency. Increases in throughput would be less compelling if they came at the cost of high latency. Figure 5(a) graphs latency versus throughput for the OO7 RW workload with a single store. For base Fabric, latency increases sharply around 500 tx/sec as high load overwhelms the shared store. The JPA system has a more difficult time meeting throughput demands and cannot reach even 100 tx/sec. With smaller read sets, the warranties system delivers higher throughput even for a single store, around 1100 tx/sec.

	Throughput	Latency (ms)
Base system	52	481
State warranties only	53	284
Computation warranties	515	30

Table 2: Top-N benchmark, maximum throughput (tx/s)

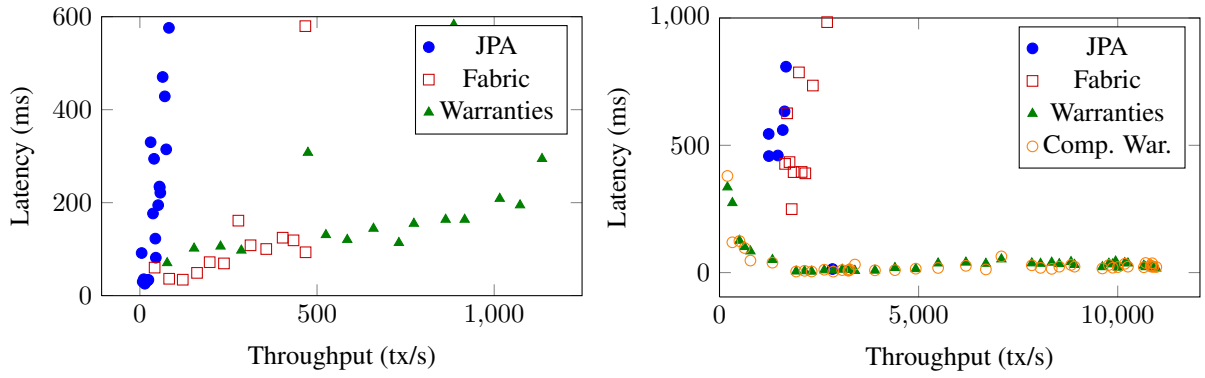
The tradeoff for the increase in throughput is increased write latency. Average write latency with warranties almost 10 times higher than in base Fabric at low throughput. However, this delay allows total throughput to scale much better. At high throughput, average write latency is comparable between the two systems.

Figure 5 plots latency versus throughput for the CMS implementation configured for one store. Although JPA achieves lower throughput than base Fabric, its performance profile looks similar to Fabric's. This is unsurprising: both are performing many of same operations to commit each transaction. Although the JPA implementation enforces weaker consistency, Fabric's precise object invalidation helps performance with aborts.

Warranties, both with and without computational warranties enabled, far outperform Fabric and JPA. The access control functions we designated as memoized turn out not to have a measurable impact on the computational warranties system. They are relatively cheap to evaluate on cached objects, and the bookkeeping for computational warranties adds no noticeable overhead. The read-mostly workload permits warranty terms that greatly reduce the number of prepared objects, enabling many more transactions to be committed. At 11k tx/sec—the maximum 10 quad-core workers could generate—the store still had less than 50% CPU utilization for both warranty-based systems.

7.7 Computation warranties

To further evaluate the impact of computation warranties, we ran the top-N benchmark with Fabric, state warranties, and with computation warranties. Because the performance of the recursive top-N strategy on Fabric and on state warranties was very poor, we used an alternate implementation that performed better on those configurations. Table 2 shows the average across three runs of the maximum throughput and the corresponding latency. Computation warranties improve throughput by an order of magnitude.



(a) OO7, RW Workload

(b) CMS

Figure 5: OO7 throughput vs. latency on a single store. Warranties increase throughput and reduce average latency.

8 Related work

Many mechanisms for enforcing concurrency control have been proposed in the literature: locks, timestamps, versions, logs, leases, and many others [27, 18, 28, 38, 5, 17]. Broadly speaking, these can be divided into optimistic and pessimistic mechanisms. The monograph by Bernstein, Hadzilacos, and Goodman provides a broad overview from the perspective of databases [6]. Warranties are an optimistic technique, as they allow multiple clients to operate on shared data concurrently.

Traditionally, most systems adopted *serializability* or *linearizability* as the gold standard of strong consistency [35, 6, 20]. But many recent systems have sacrificed serializability in pursuit of scalable performance. Vogels [45] discusses this trend and surveys various formal notions of *eventual consistency*. There is much prior work on weak consistency models that provide some sort of consistency guarantee that is weaker than serializability; for example, causal consistency (e.g., [37, 33]) and *probabilistically-bounded staleness* [4]. Because this paper is about strong consistency, we do not discuss this prior work in depth.

Leveraging application-level information to guide implementations of transactions was proposed by Lamport [27] and explored extensively in Garcia-Molina's work on *semantic types* [16], as well as recent work on *transactional boosting* [21] and *coarse-grained transactions* [25]. Unlike warranties, these systems use mechanisms based on commuting operations. A related approach is *red–blue consistency* [30] in which red operations must be performed in the same order at each node and blue operations may be reordered.

Like warranties, Sinfonia [2] aims to reduce client-server round trips without hurting consistency. It does this through *mini-transactions*, in which a more general computation is piggybacked onto the prepare phase. This optimization is orthogonal to warranties.

As discussed in Section 3.2, warranties borrow from leases the idea of using time, though there are several important differences. The idea of expiring guarantees occurs in a simpler form even earlier in Lampson's global directory service [29]. Client caches have entries with server-specified expiration times, and servers cannot update the caches until they expire.

A generalization of leases, *promises* [19, 23] is a middleware layer that allows clients to specify resource requirements via logical formulas. A resource manager considers constraints across many clients and issues time-limited guarantees about resource availability. Scalability of promises does not seem to have been evaluated.

The tracking of dependencies between computation warranties, and the incremental updates of those warranties while avoiding unnecessary invalidation, is close to the update propagation technique used in self-adjusting computation [1], realized in a distributed setting. Incremental update of computed results has also been done in the setting of map-reduce [7].

9 Conclusions

Strong consistency tends to be associated with the very real performance problems of pessimistic locking. While optimistic concurrency control mechanisms deliver higher performance for typical workloads, read prepares on popular objects are still a performance bottleneck. Warranties generalize OCC in a way that reduces the read-prepare bottleneck. Warranties address this bottleneck by allowing stores to distribute warranties on popular objects, effectively replicating their state throughout the system. Warranties can delay update transactions, but our results show that the delay is acceptable. Effectively, warranties generalize OCC in a way that adjusts the balance of power between readers and writers, substantially increasing overall performance. Computation warranties improve performance further by supporting `memcached`-like reuse of computations—but with strong consistency.

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