Montage: A General System for Buffered Durably Linearizable Data Structures

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Abstract

The recent emergence of fast, dense, nonvolatile main memory suggests that certain long-lived data might remain in its natural pointer-rich format across program runs and hardware reboots. Operations on such data must be instrumented with explicit write-back and fence instructions to ensure consistency in the wake of a crash. Techniques to minimize the cost of this instrumentation are an active topic of research.

We present what we believe to be the first general-purpose approach to building buffered durably linearizable persistent data structures, and a system, Montage, to support that approach. Montage is built on top of the Ralloc nonblocking persistent allocator. It employs a slow-ticking epoch clock, and ensures that no operation appears to span an epoch boundary. It also arranges to persist only that data minimally required to reconstruct the structure after a crash. If a crash occurs in epoch e, all work performed in epochs e and e − 1 is lost, but work from prior epochs is preserved.

We describe the implementation of Montage, argue its correctness, and report unprecedented throughput for persistent queues, sets/mappings, and general graphs.

1. Introduction

Despite enormous increases in capacity over the years, the dichotomy between transient working memory (DRAM) and persistent long-term storage (magnetic disks and flash) has been a remarkably stable feature of computer organization. Finally, however, DRAM is approaching end-of-life. Successor technologies will be denser and much less power hungry. They will also be nonvolatile. Already, today, one can buy an Intel server with multiple terabytes of byte-addressable phase-change memory for less than $20K USD. While it is entirely possible to use nonvolatile memory (NVM) as a plug-in replacement for DRAM, nonvolatility raises the intriguing possibility of keeping pointer-rich data “in memory” across program runs and even system crashes, rather than serializing it to and from a file system or back-end database.

Crashes cause problems, however. For file systems and databases, long-established logging techniques ensure that transitions from one consistent state to another are failure atomic. For data structures accessed with load and store instructions, the cost of such logging may be prohibitively high. Moreover, the fact that caches remain volatile and may write back their contents out of program order means that data structure operations must typically issue explicit write-back and fence instructions to guarantee post-crash consistency.

Past work has established durable linearizability as the standard correctness criterion for persistent data structures [23]. This criterion builds on the familiar notion of linearizability for concurrent (non-persistent) data structures. A data structure is said to be linearizable if whenever threads perform operations concurrently, the effect is as if the operations had been performed sequentially in some order that is consistent with real time order (if operation A returns before operation B is called, then A must appear to happen before B) and with the semantics of the abstraction represented by the structure.

A persistent data structure is said to be durably linearizable if (1) it is linearizable during crash-free operation, (2) each operation persists (reaches a state that will survive a crash) between its call and return, and (3) the order of persists matches the linearization order. By introducing program-wide coordination of persistence, buffered durably linearizable data structures may reduce ongoing overhead by preserving only some consistent prefix of the history prior to a crash.

Recent publications have described many individual durably linearizable data structures and perhaps two dozen general-purpose systems to provide failure atomicity for outermost critical sections or speculative transactions (Sec. 2). The need for operations to persist before returning is a significant source of overhead in these systems. To reduce this overhead, Nawab et al. developed a buffered durably linearizable hash table (Dali [40]) that ensures persistence on a periodic (as opposed to incremental) basis. More recently, Haria et al.’s MOD project [17] proposed that programmers rely on history-preserving (“functional”) tree structures, in which each update can be persisted by updating a single root pointer, eliminating the need for logging. Memaripour et al.’s Pronto project [36] proposed that concurrent objects log their high level (abstract) operations (rather than low-level updates), together with occasional checkpoints; on a crash, they replay the portion of the log that follows the most recent checkpoint.

Inspired in part by these previous projects, we present what we believe to be the first general-purpose approach to buffered durably linearizable structures. Our system, Montage, employs a slow-running epoch clock, and ensures that no opera-
We have designed an extension to Montage that avoids even within a factor of 3 of a transient DRAM table. This is close to work—7

The past few years have seen an explosion of work on persistent memory. Montage itself is also lock-free during normal operation, though a stalled thread can arbitrarily delay progression of the persistence frontier. We have designed an extension to Montage that avoids even this more limited form of blocking; given that threads in real systems are seldom preempted for more than a fraction of a second, however, the complexity of the extension seems unwarranted in practice.

Performance experiments (Sec. 6) reveal that a Montage hash map can sustain well over 20 M ops/s on a read-heavy workload—7× as many as Dalí, 17× as many as Pronto, and within a factor of 3 of a transient DRAM table. This is close to the best one could hope for: read latency for Intel Optane NVM is about 3× that of DRAM [24].

After reviewing related work in Section 2, we provide a high-level description of Montage in Section 3. Correctness arguments appear in Section 4; implementation details appear in Section 5. Section 6 presents performance results, including an exploration of the Montage design space and a comparison to competing systems. Section 7 presents conclusions.

2. Related Work

The past few years have seen an explosion of work on persistent data structures, much of it focused on B-trees indices for file systems and databases [5, 21, 25, 31, 39, 41, 49, 54]. Other work has targeted RB trees [51], radix trees [28], hash maps [40, 46, 55], and queues [14]. Several projects persist only parts of a data structure, and rebuild the rest on recovery. Zuriel et al. [55] argue that this approach can be used for almost any implementation of a set or mapping. Unfortunately, their technique keeps a full copy of the structure in DRAM, forfeiting the much larger capacity of NVM. Montage eliminates this restriction; it also accommodates not only sets and mappings, but any abstraction that comprises items and relationships—effectively, anything that can be represented as a graph.

Several existing data structures are designed to linearize by using a single compare-and-swap (CAS) instruction to replace a portion of the structure [5, 28, 39, 40]. If the new portion is persisted before the CAS, and the updated pointer is persisted immediately after the CAS, no separate logging is required. Mahapatra et al. [33] and Haria et al. [17] apply this observa-

tion to a variety of “functional” data structures, building sets, maps, stacks, queues, and vectors. As an extension, a sequence of single-CAS steps can be used to move a structure through self-documenting intermediate stages [21, 51]. In a similar vein, hardware transactional memory can be used to modify a data structure and a log concurrently [31], or to update an entire cache line without any chance that an intermediate version will be written back to memory [25].

Izraelevitz et al. [23] provide a mechanical construction to convert any nonblocking concurrent structure into a correct persistent version. David et al. [10] describe several techniques to eliminate redundant writes-back and fences for such structures, significantly improving performance.

Beyond individual data structures, several groups have developed systems to ensure the failure atomicity of lock-based critical sections [3, 20, 22, 32] or speculative transactions [1, 4, 6, 7, 9, 15, 16, 37, 42, 43, 48, 50]. Significantly, all of these systems ensure that an operation has persisted before permitting the calling thread to proceed—that is, they adopt the strict version of durable linearizability.

The Dalí hash map [40] delays persistence, so the overhead of writes-back and fencing can be amortized over many operations while still providing buffered durable linearizability. The implementation relies on a flush-the-whole-cache instruction, available only in privileged mode on the x86, and with the side effect of unnecessarily evicting many useful lines. Our reimplementation of Dalí (used in Sec. 6) tracks to-be-written-back lines explicitly in software—as does Montage. Montage then extends delayed persistence to arbitrary data structures.

Perhaps the closest prior work to Montage, in motivation and generality, is the Pronto system of Memaripour et al. [36]. As noted in Section 1, Pronto logs high level (abstract) operations rather than low-level updates, and replays the log after a crash. Periodic checkpoints allow it to bound the length of the log, and thus recovery time. Notably, Pronto still pays the cost of persisting each operation before returning.

Montage’s use of a global epoch clock has several precedents, including implementations of software transactional memory [11, 44] and of safe memory reclamation for transient [12] and persistent [10] data structures.

3. Montage Design

Montage manages persistent payload blocks on behalf of one or more concurrent data structures. A programmer who wishes to adapt a structure to Montage must identify the subset of the structure’s data that is needed, in quiescence, to capture the state of the abstraction. A set, for example, needs to keep its items in payload blocks, but not its lookup structure. A mapping needs to keep key-value pairs. A queue needs to keep its items and their order: it might label payloads with consecutive integers from i (the head) to j (the tail). A graph can keep a payload for each vertex (each with a unique name) and a payload for each edge (each of which names two vertices).
A typical data structure maintains additional, transient data to speed up operations. A set or mapping might maintain a hash table, tree, or skip list as an index into the pile of items or pairs. A queue might maintain a linked list of pointers to items. A graph (depending on the nature of the application) might maintain a transient object for each vertex, containing a pointer to a payload for the vertex attributes, a set of pointers to neighboring vertex objects, and (if edges have large attributes) a set of pointers to edge payloads. All of this transient data must be reconstructed after a crash.

Crucially, synchronization is always performed on transient data. That is, Montage does not determine the linearization order for operations on a data structure. Rather it ensures that the persistence order for payloads is consistent with the linearization order provided by the transient structure. More specifically, it divides execution into epochs in such a way that every epoch boundary represents a consistent cut of the happens-before relationship among operations; it then arranges, in the wake of a crash, to recover all managed data structures to their state as of some common epoch boundary.

3.1. API

The Montage API for C++ is shown in Figure 1. An example of a lock-based hash table is shown in Figure 2.

Any operation that creates or updates payloads must make itself visible to Montage by calling BEGIN_OP or BEGIN_OP_AUTOEND. It indicates completion with END_OP. Read-only operations can skip these calls, though they must still synchronize on the transient data structure. Payloads are created and destroyed using PNEW and PDELETE. PRETIRE and PRECLAIM take the place of PDELETE for nonblocking memory management (Sec. 3.3). Existing payloads are accessed with get and set methods, created by the GENERATE_FIELD macro; get returns a const reference to the field; set updates the field and returns a (possibly altered) pointer to the payload as a whole.

To support the epoch system, Montage labels all payloads with the epoch in which they were created or most recently modified. An operation in epoch $e$ that wishes to modify an existing payload can do so “in place” if the payload was created in $e$; otherwise, Montage creates a new payload with which to replace it. The set methods enforce this convention by returning a pointer to a new or copied payload, as appropriate.

Because epochs are long (10–100 ms), “hot” payloads are typically modified in place. When a new copy is created, however, an operation must re-write any pointers to the payload found anywhere in the structure. For this reason, it is important to minimize the number of pointers to a given payload found in transient data. It is even more important to avoid long chains of pointers in persistent data: otherwise, a change to payload $p$, at the end of a long chain, would require a change to the penultimate payload $p'$, which would in turn require a change to its predecessor $p''$, and so on. A similar observation is made by the designers of MOD [17].

Because calls to get are invisible to recovery, they can safely be made outside the bounds of BEGIN_OP and END_OP (subject to transient synchronization). Calls to PNEW can also be made early, so long as the payloads they return are passed as parameters to BEGIN_OP, so they can be properly labeled.

3.2. Periodic Persistence

The key task of Montage is to ensure that operations persist in an order consistent with their linearization order. Toward that end, the system ensures that

1. all payloads created or modified by a given operation are labeled with the same epoch number;
2. all payloads created or modified in a given epoch $e$ persist together, instantaneously, when the epoch clock ticks over from $e + 1$ to $e + 2$; and
3. each update operation linearizes in the epoch in which it created payloads.

Figure 1: C++ API.
class Payload
{...
};

PDELETE(payload);
BEGIN_OP_AUTOEND(new_node->payload);
payload = payload->set_val(v);
GENERATE_FIELD(K, key, Payload);
payload = PNEW(Payload, key, val);

Property 1 is ensured by the set and PNEW methods, as described in Section 3.1. Note that an operation that begins in epoch $e$ can continue to create and modify payloads in that epoch, even if the clock ticks over to $e + 1$.

Property 2 is enforced by Montage’s recovery routines: if a crash occurs in epoch $e$, those routines discard all payloads labeled $e$ or $e − 1$, but keep everything that is older. Note that this convention requires that deletion be delayed. If a payload created or updated in epoch $b$ is passed to PDELETE in epoch $e > b$, the PDELETE method creates an “anti-payload” labeled $e$. If a crash occurs before $e + 2$, the anti-payload will be discarded and the original payload retained. If a crash occurs immediately after the tick from $e + 1$ to $e + 2$, the anti-payload will be discovered during recovery and both it and the original payload will be discarded. If execution proceeds without a crash, the original payload will be reclaimed when the epoch advances from $e + 2$ to $e + 3$; the anti-payload will be reclaimed when the epoch advances from $e + 3$ to $e + 4$.

Property 3 is the responsibility of the transient data structure built on top of Montage. Lock-based operations are easy: no conflicting operation can proceed until we release our locks, and we can easily pretend that all updates happened at the last call to set or PNEW. For nonblocking structures, a similar guarantee can be made if every operation linearizes on a statically identified compare-and-swap (CAS) instruction that also modifies an adjacent counter (as is often used to avoid ABA anomalies). One first reads some variable $x$, then double-checks the epoch clock (the CHECK_EPOCH method exists for this purpose), and only then attempts a CAS on $x$. If the CAS succeeds, it can be said to have occurred at the time of the CHECK_EPOCH call. Note that this strategy generally requires read-only operations on the same structure to be modified by replacing their linearizing read with a CAS that updates the adjacent count: otherwise a read that occurs immediately after an epoch change might observe an update from the previous epoch as not yet having occurred. For cases in which this modification is undesirable (e.g., because reads vastly outnumber updates), we use a variant of the double-compare-single-swap (DCSS) software primitive of Harris et al. [27]) to update a location while simultaneously verifying the current epoch number. A compatible read primitive performs no store instructions (and thus induces no cache evictions) so long as no DCSS is currently in progress in another thread (if one is, the read helps the DCSS complete).

As an assist to programmers in ensuring property 3, Montage raises an exception whenever an operation running in epoch $e$ reads a payload created in some epoch $e' > e$. In most cases, programmers can ensure that this exception will never arise. In other cases, the operation may respond to the exception by rolling back what has done so far and starting over in the newer epoch. In special cases, an operation can ignore the exception or use get_unsafe methods to avoid generating it in the first place (the new data might, for example, be used only for semantically neutral performance enhancement).

In support of these properties, the epoch-advancing mechanism at the end of epoch $e$
• waits until no operation is active in epoch $e − 1$;
• reclaims all payloads deleted in epoch $e − 2$ and all anti-payloads created in epoch $e − 3$;
• explicitly writes back all payloads created or modified in epoch $e − 1$;
• waits for the writes-back to complete; and
• updates and writes back the epoch clock.

Further details appear in Section 5.

Figure 2: Simple lock-based hash table example (Montage-related parts highlighted).

1 class HashTable{
2 // Payload class
3 class Payload : public PBlk{
4 GENERATE_FIELD(K, key, Payload);
5 GENERATE_FIELD(V, val, Payload);
6 }
7 // Transient index class
8 struct ListNode{
9 // Transient-to-persistent pointer
10 Payload payload = nullptr;
11 // Transient-to-transient pointers
12 ListNode next = nullptr;
13 void set_val_wrapper(V v) {
14 payload = payload->get_val();
15 }
16 ListNode(K key, V val) {
17 payload = PNEW(Payload, key, val);
18 }
19 ~ListNode() {
20 PDELETE(payload);
21 }
22 // get() methods omitted
23 }
24 // Insert, or update if the key exists
25 optional<V> put(K key, V val, int tid) {
26 size_t idx = hash_fn(key); // Transient index class
27 ListNode new_node = new ListNode(key, val);
28 std::lock_guard lk(buckets[idx].lock);
29 BEGIN_OP_AUTOEND(buckets[idx]->payload);
30 ListNode curr = buckets[idx].head.next;
31 ListNode prev = &buckets[idx].head;
32 while (curr) {
33 if (curr_key == key) {
34 return curr->get_val();
35 } else if (curr_key > key) {
36 new_node->next = curr;
37 prev->next = new_node;
38 return new_node;
39 } else {
40 prev = curr;
41 curr = curr->next;
42 }
43 }
44 }
45 // while
46 prev->next = new_node;
47 return new_node;
48 }
49 }
50

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3.3. Nonblocking Data Structures

As described in Section 3.2, Montage is compatible with non-blocking operations that employ special CAS or read primitives to ensure that linearization occurs in the epoch in which any payloads were created or modified.

In the general case, a structure that uses the OldSeeNew-Exception to keep its linearization order consistent with epoch order may find that the resulting restarts make it lock-free or obstruction-free, rather than wait-free. Still, nothing in Montage precludes lock freedom. At the same time, while Montage never indefinitely delays an operation unless some other operation has made progress, a stalled operation can indefinitely delay the progress of persistence.

We have designed (but not yet implemented) a version of Montage that allows the epoch clock (and thus the persistence frontier) to advance in a nonblocking fashion. Montage already maintains, internally, an array that indicates, for each thread, whether that thread is actively executing a data structure operation, and, if so, in which epoch. (It is by scanning this array that the epoch-advancing mechanism knows whether it can proceed.) The key to nonblocking persistence is to augment this array with a “serial number” for the current operation, and an indication of whether that operation is active, committed, or aborted, much as nonblocking object-based software transactional memory systems track the status of transactions [13, 19, 34, 35, 47]. Each payload is then labeled not only with an epoch number, but with the thread id and serial number of its creator. To advance the epoch, we scan the array and abort any operation that stands in our way by CAS-ing its status from “active” to “aborted.” Each data structure operation, for its part, ends by CAS-ing its status from “active” to “committed” and, if the epoch has advanced, performing a write-back and fencing that status. Recovery routines, in the wake of a crash, discard any payloads—even in old epochs—whose creating operations were aborted.

Nonblocking structures may need to use safe memory reclamation (SMR) techniques, such as epoch-based reclamation [12] or hazard pointers [38], to avoid creating dangling pointers when deleting blocks to which other threads may still hold references. In such structures, the actual reclamation of a block may be occur outside the scope—or even the epoch—of its deleting operation. Simply delaying the PDELETE of a payload to the reclamation of some corresponding transient block does not suffice, because transient limbo lists belonging to SMR are lost after a crash. Montage provides PRETIRE and PRECLAIM operations to handle this situation.

Typically, PRETIRE is called when a payload is “detached” from the shared structure, and PRECLAIM is called upon the destruction of its transient parent, when no references to the payload remain outside the memory manager. After a crash in epoch \( e \), a payload PRETIRE\(e \)d in or before \( e - 2 \) but not PRECLAIM\(e \)d can safely be reclaimed.

4. Correctness

We argue that Montage (1) preserves the linearizability of a structure implemented on top of it, (2) adds buffered durable linearizability, and (3) preserves lock freedom.

Each concurrent data structure serves to implement some abstract data type. The semantics of such a type are defined in terms of legal histories—sequences of operations, with their arguments and return values. The implementation is correct if it is linearizable, meaning that every concurrent history (with overlapping calls and returns from different threads) is equivalent to (has the same operations as) some sequential history that is consistent with real-time order (if \( a \) returns before \( b \) is called in the concurrent history, then \( a \) precedes \( b \) in the sequential history) and that represents a valid operation sequence for the data type.

We can define the abstract state of a data type, after a finite sequence of operations, as the set of sequences that are permitted to extend that sequence according to the type’s semantics. Suppose, then, that data structure \( S \) is a correct implementation of data type \( T \), and that \( s \) is a quiescent concrete state of \( S \) (the bits in memory at some point when no operations are active). We can define the meaning of that state, \( \mathcal{M}(s) \), as the state of \( T \) after the sequence of abstract operations corresponding to (a linearization of) the operations performed so far on \( S \).

We assume that the programmer using Montage obeys the following well-formedness constraints:

1. Each data structure \( S \), implemented on top of Montage, is linearizable when Montage itself is disabled and crashes do not occur. More specifically, assume that (a) \( \text{PNEW} \) and \( \text{PDELETE} \) are implemented as ordinary new and delete; (b) \( \text{get} \) and \( \text{set} \) are ordinary accessor methods, and \( \text{set} \) never copies a payload; (c) \( \text{BEGIN\_OP} \) and \( \text{END\_OP} \) are no-ops; and (d) the OldSeeNewException never arises. Under these circumstances, the structure is linearizable.

2. Any synchronization required for linearizability is performed solely on transient data—accesses to payloads never participate in a data or synchronization race.

3. All accesses to payloads are made through \( \text{get} \) and \( \text{set} \). Each operation that modifies the data structure (a) calls \( \text{BEGIN\_OP} \) before \( \text{set} \) (passing as arguments any previously created payloads), (b) calls \( \text{END\_OP} \) after completing all its \( \text{set} \)s, and (c) ensures that between its last call to \( \text{set} \) or \( \text{CHECK\_EPOCH} \) and its linearization point, no conflicting operation can linearize.

4. Whenever \( \text{set} \) returns a pointer to a payload different than the one on which it was called, the calling operation replaces every pointer to the old payload in the structure with a pointer to the new payload.

5. There exists a mapping \( D \) from sets of payloads to states of \( T \) such that whenever \( S \) is quiescent, \( \mathcal{M}(s) = D(p) \), where \( s \) is the concrete state of \( S \) and \( p \) is the current set of payloads.

6. The recovery routine for \( S \), given a set of payloads \( r \), con-
structs a concrete state \( t \) such that \( \mathcal{M}(t) = \mathcal{Q}(r) \).

### 4.1. Linearizability

**Lemma 1.** A well-formed, linearizable concurrent data structure, implemented on top of Montage, remains well-formed and linearizable when Montage is enabled.

**Proof.** Constraint 4 ensures that any payload cloned by Montage is reattached to the structure wherever the old payload appeared. Since access to payloads is race-free (Constraint 2), this re-attachment is safe. Throws of the OldSeeNewException will be harmless: they exist simply to simplify compliance with Constraint 3; any operation that already satisfies that constraint can safely ignore the exception. Finally, given the mapping \( \mathcal{Q} \) from payloads to abstract state (Constraint 5), we can easily create a \( \mathcal{Q}' \) that ignores both the old versions of cloned payloads and any payloads for which an anti-payload exists. These are the only effects of enabling Montage that are visible to the structure during crash-free execution. □

**Theorem 1.** A Montage data structure \( S \) remains linearizable when epoch advancing operations are added to its history.

**Proof.** Let \( a_e \) denote the operation that advances the epoch from \( e - 1 \) to \( e \). Consider a linearization order for \( S \) itself, as provided by Lemma 1. Constraint 3 ensures that the linearization point of any update operation in this order occurs between events \( a_e \) and \( a_{e+1} \), making it easy to place these events into the linearization order. A read-only operation, moreover, has no forward or anti-dependences on the epoch clock, and so cannot participate in any circular dependence with respect to the epoch advancing events. □

### 4.2. Buffered Durable Linearizability

**Theorem 2.** A well formed, linearizable concurrent data structure, running on Montage, is buffered durably linearizable.

**Proof.** We need to show that in any execution \( H \) containing a crash \( c \), the state of the data structure after recovery reflects some consistent prefix of the linearized pre-crash history. Suppose that \( c \) occurs in epoch \( e \) of \( H \). If \( e \leq 2 \), recovery will restore the initial state of the system, which reflects the null prefix of execution. If \( e > 2 \), Montage will discard all payloads created in epochs \( e \) and \( e - 1 \), preserving those in existence as of \( a_{e-1} \), and will pass these to the structure’s recovery routine. This routine, by Constraint 6, will construct a new concrete state \( t \) such that \( \mathcal{M}(t) = \mathcal{Q}(r) \), where \( r \) is the set of payloads it was given. But \( r \) is precisely the set of payloads created by operations that linearized prior to \( a_{e-1} \). If execution had reached quiescence immediately after those operations, Constraint 5 implies that the concrete state \( s \) of \( S \) would have been such that \( \mathcal{M}(s) = \mathcal{Q}(r) \). Thus the post-recovery state \( t \) reflects a consistent prefix of the linearized pre-crash history. □

### 4.3. Liveness

**Theorem 3.** Montage is lock free during crash-free execution.

**Proof.** The only loop in Montage lies within \( \text{BEGIN\_OP} \), where an update operation seeks to read the epoch clock and announce itself as active in that epoch, atomically. Each retry of the loop implies that the epoch has advanced. If we assume that the epoch advancing operation (which need not be nonblocking) always waits until at least one operation has completed in the old epoch, then an operation can be delayed in \( \text{BEGIN\_OP} \) only if some other operation has completed. The OldSeeNewException, similarly, will arise (and cause some operations to start over) only if the epoch has advanced. □

### 5. Implementation Details

Figure 3 shows pseudocode for Montage’s core functionality. Transient data structures include an “operation tracker” that indicates, for each thread in the system, the epoch of its active operation (if any), and lists of payloads to be persisted and freed at future epoch boundaries. The latter are logically indexed by epoch, but only the most recent 2 or 3 are needed. For simplicity, Montage maintains four sets of lists, and indexes them using the 2 low-order bits of the epoch number. For convenience, each thread also caches the epoch of its currently active operation (if any) in thread-local storage.

Aside from the epoch clock itself, payloads are the only data allocated in NVM. Each payload indicates the epoch in which it was created and whether it is new (\( \text{ALLOC} \)), a replacement of an existing payload (\( \text{UPDATE} \)), or an anti-payload (\( \text{DELETE} \)). \( \text{ALLOC} \) payloads are created only in \( \text{PNEW} \). \( \text{UPDATE} \) payloads are created only in \( \text{set} \) (when we discover that the block being written was created in an earlier epoch, and cannot be updated in place). In lock-based data structures, \( \text{DELETE} \) payloads are created only in \( \text{PDELETE} \); they live for exactly two epochs. until the payload the payload nullifying can safely be reclaimed. With nonblocking memory management, \( \text{DELETE} \) payloads are created only in \( \text{PRETIRE} \); they live for two epochs after the corresponding \( \text{PRECLAIM} \) call.

#### 5.1. Storage Management

Space for payloads in Montage is managed by a variant of the Ralloc persistent allocator [2]. Ralloc is in turn based on the nonblocking allocator of Leite and Rocha [29]. Ralloc has very low overhead and excellent locality during crash-free operation. Almost all metadata is kept in transient memory, and most allocation and deallocation operations perform no write-back or fence instructions.

In its original form, Ralloc performs garbage collection after a crash to identify the blocks that are currently in use; all others are returned to the free list. For Montage, we modified the recovery mechanism to simply peruse all blocks, and to keep all and only those that are labeled as having been created at least two epochs ago. (These blocks will of course have
been written back at some previous epoch boundary. Montage passes the recovered blocks (i.e., payloads) to the application data structure, which is then responsible for rebuilding transient structures. To facilitate parallel recovery, the application can request that the blocks be returned via k separate iterators, to be used by k separate application threads.

5.2. Persistence, Epoch, and Reclamation Strategy

A wide variety of concrete designs could be used to flesh out the pseudocode of Figure 3. Natural questions include:

- Should the advance_epoch function be called periodically by application (worker) threads—e.g., from within the API calls—or should it be called by a background thread?
• Once \texttt{advance\_epoch} has been called, should it be executed by a single thread, or should it be parallelized? (The Pronto system, a possible inspiration, can be configured to perform writes-back on the sister hyperthread of the worker that wrote the data [36].)

• Is the answer to the previous question the same for both writes-back and storage reclamation? Perhaps some tasks are better performed on the cores where payloads or payload lists are likely to be in cache?

• Should all writes-back for a given epoch be delayed until the end, or does it make sense to start some of them earlier? One might, for example, employ a circular buffer in each worker, and issue writes-back one at a time, all at once, or perhaps half a buffer at a time, as the buffer fills.

• How long should an epoch be? Should it be measured in time, operations performed, or payloads written?

We performed a series of experiments to evaluate the impact on performance of various answers to these questions. A summary of the results appears in Section 6.2. The short answer is that it seems to make sense, for the data structures we have explored to date, and on the 2-socket Intel server in our lab, to have a single background thread that is responsible for all the work of \texttt{advance\_epoch}, and to have it perform this work every 10–100 ms.

6. Experimental Results

In this section, we report experiments on queues, maps, graphs, and memcached to evaluate Montage’s performance and generality, and to answer the following questions:

• What is the best way to configure Montage? (Sect. 6.2)

• How does Montage compare to prior special- and general-purpose systems, and to baseline transient structures? (Secs. 6.3–6.5)

• What is the cost of recovery? (Sec. 6.6)

6.1. Hardware and Software Platform

All tests were conducted on a Linux 5.3.7 (Fedora 30) server with two Intel Xeon Gold 6230 processors, with 20 physical cores and 40 hyperthreads in each socket—a total of 80 hyperthreads. Threads in all experiments were pinned first one per core on socket 0, then on the extra hyperthreads of that socket 0, and then on the second socket. Each socket has 6 channels of 128 GB Optane DIMMs and 6 channels of 32 GB DRAMs. We use ext4 to map NVM pages in direct access (DAX) mode. The source code of Montage is available at https://github.com/urcs-sync/Montage.

Systems and structures tested include the following:

\textbf{Montage} – as described in previous sections.

\textbf{Friedman} – the persistent lock-free queue of Friedman et al. [14].

\textbf{Dali} – our reimplementation of the buffered durably linearizable hash table of Nawab et al. [40].

\textbf{SOFT} – the lock-free hash table of Zuriel et al. [55], which persists only semantic data but keeps a full copy in DRAM.

\textbf{MOD} – persistent structures (here, queues and hash maps) as proposed by Haria et al. [17], who leverage history-preserving trees to linearize updates with a single write.

\textbf{Pronto-Full} and \textbf{Pronto-Sync} – the general-purpose system of Memaripour et al. [36], which logs high-level operation descriptions that can be replayed, starting from a checkpoint, to recover after a crash. We test both the synchronously logged and (on \leq 40 threads) the “full” (asynchronous) version.

\textbf{Mnemosyne} – the general-purpose, pioneering system of Volos et al. [50], which adds persistence to the TinySTM transactional memory system [44].

For comparison purposes, we also include:

\textbf{DRAM (T) and NVM (T)} – high quality transient data structures built on DRAM and NVM, respectively, with no persistence support.

\textbf{Montage (T)} – a variant of Montage that still places payloads in NVM, but elides all persistence operations (no buffering, write-back instructions, delayed deletion, or epoch advance).

6.2. Sensitivity to Design Alternatives

As noted in Section 5.2, there is a very large design space for the outline given in Figure 3. In Figure 4, we show the performance of a Montage hash map across several design dimensions. Each narrow bar indicates total throughput for 40 threads running on a single processor of our test machine. Each thread performs lookup, insert, and delete operations in a 2:1:1 ratio. The table has one million buckets. It begins half full and remains so, as keys are drawn from a million-element range. In each group of bars, the epoch length varies from 1 \mu s to 15s. We used time to measure epoch length because it does not vary across threads.

We consider three main strategies for write-back. In \textbf{DirectWB}, each update operation initiates the write-back of its payloads immediately after completing. This strategy is somewhat risky on current Intel processors: the clwb (cache line write-back) instruction actually evicts the line, raising the possibility of an unnecessary subsequent last-level cache miss if the line is still in the working set. (Future processors are expected to retain the line in shared mode.) In \textbf{PerEpoch}, each thread maintains a buffer in which it stores the address and length of every written payload. These are saved for write-back at the end of the next epoch. In the intermediate \textbf{BufferedWB} strategy, each buffer holds only 1000 entries, half of which are written back when that capacity is reached.

For \textbf{BufferedWB}, we tried letting each worker perform its own writes-back (Worker), or arranging for these to happen on the sister hyperthread, which shares the L1 cache (PerThread). For \textbf{PerEpoch}, we tried performing the writes-back on the sister hyperthreads (PerThread) or in a single background thread that empties all the buffers (OneThread).

Memory reclamation always has to be delayed for two epochs, as explained in Section 3.2. We experimented with strategies in which payloads were always reclaimed on the core on which \texttt{PDELETE} was called, but any benefits of locality
were outweighed by the cost of global synchronization. Fortunately, even though it relies on thread-local free lists, Ralloc is able to rebalance these very efficiently; it imposes very little penalty for deallocating all blocks in the epoch-advancing thread. For comparison purposes, we also ran experiments Montage (T) and with an (unsafe) variant of BufferedWB that does not delay reclamation.

As shown in Figure 4, OneThread generally beats Worker and PerThread, particularly given that the latter requires so many extra pipeline resources. PerEpoch generally beats BufferedWB; this may be due to the impact of working set eviction or to the fact that, by the end of the epoch, many payloads have already been written back implicitly. Overall, PerEpoch+OneThread is clearly the winning strategy. A single thread turns out to have ample bandwidth for the task, even given the cache misses it suffers while perusing per-thread buffers.

Note that most groups of bars slope upward with very long epochs. Given our workload, when epochs are measured in seconds, most existing payloads are deleted early in the epoch; subsequent deletions tend to be “same-epoch” payloads, and can be reclaimed without delay. This is verified both by the fact that “Montage (T)” has no curve to its bar group and by a follow-up experiment showing that the rise in performance comes later when the key range is larger. The closeness in height of the final two bar groups suggests that most of Montage’s overhead is due to memory management, not to writes-back. In PerThread and DirectWB, the benefit of very short epochs, relative to medium-length, presumably reflects the fact that buffers are likely to remain in the L1 or L2 cache if epochs are extremely short.

In other experiments (not shown), we varied several additional parameters, including buffer sizes and emptying fractions for BufferedWB, and synchronization mechanisms for PerThread. None of these produced significantly different results. For example, in experiments in this paper, Montage is configured with per-thread, whole-epoch buffers, an epoch length of 50 ms, and a single background thread responsible for epoch advance, write-back, and memory reclamation.

### 6.3. Performance Relative to Competing Systems

We have benchmarked Montage against the data structures and systems listed in Section 6.1, using queue and hash map structures. Results appear in Figure 5. The Montage queue employs a single lock; the Montage hash map has a lock per bucket. In work not reported here, we have developed nonblocking linked lists, queues, and maps, and various tree-based maps. In Section 6.5 we describe the implementation of a general graph, with operations to add, remove, and update vertices and edges.

The queue microbenchmark runs a 1:1 enqueue:dequeue workload. For the map we run three different workloads—write-dominant (0:1:1 get:insert:remove), read-write (2:1:1 get:insert:remove), and read-dominant (18:1:1 get:insert:remove), with 0.5 million elements preloaded in 1 million hash buckets. The size value in queues and maps is 1 KB. The key in maps ranges from 1 to 1 million, converted to string and padded to 32 B. The benchmarks run between 1 and 90 threads. Each workload runs for 30 seconds. Results were averaged over 3 trials for each data point.

As shown in Figure 5, Montage data structures generally perform as fast as transient structures running on NVM (they may even outperform NVM (T), given transient indexing in DRAM). Compared to DRAM (T), Montage adds as little as 30% overhead in queues, and less than an order of magnitude on the highly concurrent hash table (less than 70% at low thread counts). With the exception of SOFT, Montage also outperforms all tested persistence systems on all four workloads. The Montage queue provides more than 2× the throughput of Friedman et al.’s special-purpose queue, and is more than an order of magnitude faster than the MOD, Pronto, and Mnemosyne queues. For hash maps, Montage runs more than 2× faster than MOD,2 4×–30× faster than Dali and Pronto, and nearly two orders of magnitude faster than Mnemosyne on the write-dominant and read-write workloads. On the read-dominant workload, Montage still has around 2× the throughput of MOD at most thread counts.

The exceptional case is SOFT, which maintains—and reads from—a full copy of the data in DRAM. Nonetheless, Montage is close or outperforms SOFT at low thread counts and on the read-dominant workload, and still achieves more than 1/3 the throughput of SOFT at high thread counts. The downside is that by keeping a full copy in DRAM, SOFT loses the ability to take full advantage of the 10× additional capacity of NVM. Interestingly, Montage and NVM (T) stop scaling at 12 and 20 threads on the write-dominant and read-write workloads, which may reflect multithreading contention in NVM’s write combining buffer and write pending queues [52].
Memory Configuration  In all our experiments, we allow Linux to allocate DRAM across the two sockets of the machine according to its default policy. NVM, however, must be manually configured. In the experiments of Figure 5, we interleaved it across the sockets (dm-stripe with a 2 MB chunk size) [45]. In separate experiments, we configured the sockets as separate domains, and placed all Montage’s payloads on socket 0. With threads pinned as before (numbers 40 and up on socket 1), results for the read-write and read-dominant hash tables are shown in Figure 6. With 50% writes, Montage scales better before 40 threads on the first socket’s NVM than on interleaved NVM, but drops heavily once threads cross sockets. NVM (T) is also affected. A possible explanation to the drop: frequent, slow remote writes occupy NVM bandwidth and block other accesses [52]. This cost is amortized and mitigated by the doubled number of DIMMs if NVM is interleaved across the sockets. Consistent to the explanation, the read-dominant workload behaves more smoothly while crossing sockets. The graph for the write-dominant workload (not shown here) is similar to Figure 6a. Queues show no significant difference from the interleaved case.

Payload Size  To assess the impact of operation footprint on relative performance, we repeated our queue and read-write hash table experiments with a single thread but with payloads varying from 16 B to 4 KB. Results appear in Figure 7.

As in the previous section, Montage outperforms all competitors but SOFT. This is also the case on write-dominant and read-dominant workloads (not shown). Interestingly, in the
write-heavy case, the SOFT curve drops more sharply than the Montage curve, and crosses over at just 256 B: the overhead of (strict) durable linearizability increases with larger payloads, while Montage benefits more from its buffering.

### 6.4. Hash Map Validation Using memcached

To confirm the data structure results in a more realistic application, we use Montage to persist a variant of memcached developed by Kjellqvist et al. [26]. This variant links directly to a multithreaded client application, dispensing with the usual socket-based communication. It was appealing for our experiments because the authors had already converted it to use Ralloc instead of the benchmark’s own custom allocator.

Figure 10 compares the performance of the resulting (fully persistent, recoverable) version of memcached to the transient version of Kjellqvist et al., placing items on DRAM or on NVM. Here the YCSB-A workload [8], running on 1 million records, consists of 2.5 million read and 2.5 million update operations, evenly distributed to each thread. Data points reflect the average of three trials. The results shown are for interleaved NVM; results with all data on socket 0 were very similar. As in the microbenchmark results, Montage performs within a small constant factor of purely transient structures.

### 6.5. Generality in Graphs

As noted in Section 3.1, it is important in Montage to avoid long chains of pointers. To build a persistent graph, we therefore arrange for edge payloads to point to their endpoint vertices, but not vice versa. A more conventional representation of connectivity is then kept in a transient structure, with the (typically large) edge and vertex attributes appearing only in NVM payloads. We regard the feasibility of building a graph in Montage as a strong indication of the system’s generality.

Using our Montage graphs, we compare performance (as in the memcached experiments) to transient graphs placed in DRAM or NVM. Figure 8 shows results for a microbenchmark that performs a mix of AddEdge, RemoveEdge, GetEdge, and ClearVertex operations. The first three of these take two vertex IDs as source and destination; the fourth deletes a vertex and removes all its in- and out-edges.

To initialize the graph, for each vertex \( v \in V \), we sample \( n \sim N(\mu = 10, \sigma = 3) \) and create \( n \) edges \((v, v')\), with \( v' \sim U(0, |V| - 1) \). By maintaining a small average vertex degree, this approach avoids very large atomic operations. Indeed, when ClearVertex is called less often (right half of Fig. 8), overall throughput is higher but the constant, per-operation component of Montage’s overhead has a relatively higher impact, and the gap between Montage and the transient structures is larger.

### 6.6. Recovery Time

To assess the overhead of recovery in Montage, we measured both hash map and graph examples. In the hash map case, we initialized the table with 2–64 million 1 KB elements, leading to a total payload size of 1–32 GB. With 1 recovery thread, Montage recovers the 1 GB data set in 0.7 s and the 32 GB data set in 41.9 s. With 8 recovery threads, it takes 0.4 and 13.8 s, respectively. Improving the scalability of recovery is a topic for future work.

As a second example, we compared the recovery time of a large Montage graph (the SNAP Orkut dataset [30, 53], a social network of \( \sim 3 \) M vertices and 117 M edges) to the time required to construct the same graph from a file of adjacency lists. The dataset is partitioned into many files, each of which uses a custom binary format that eliminates the need for string manipulation. Montage recovery is handled much like the parallel I/O: vertices and edges are added back to the graph in parallel. Because recovery is an internal graph operation, however, much of the locking can be elided by cyclically distributing vertices among threads, each of which creates a set of edge buffers to pass to other threads. Figure 9 demonstrates that recovery is even faster than reconstruction on DRAM at low thread counts, and takes roughly as long as reconstruction on NVM after 16 threads. Crucially, the Montage implementation has the advantage of supporting small changes to the graph without the need orchestrate persistence via file I/O.

### 7. Conclusions

We have introduced Montage, the first general-purpose system for buffered durable linearizability of persistent data structures.
In comparison to systems that are (strictly) durably linearizable, Montage moves write-back and, crucially, fencing off the critical path of the application. Montage is built on top of the Ralloc nonblocking persistent allocator [2], which avoids both writes-back and fences in most allocation and deallocation operations. Nonblocking data structures remain nonblocking when implemented on top of Montage, though preempted threads can stall the advance of the persistence frontier.

Experiments with multiple data structures—including memcached’s hash table—confirm that Montage dramatically outperforms prior general-purpose systems for persistence. It also outperforms—or is competitive with—existing special-purpose persistent data structures. In many cases, in fact, it rivals the performance of traditional transient data structures configured to use NVM instead of DRAM. This is generally the best performance one could hope for.

In most of our experiments, Montage was used to persist data structures used by a single multithreaded application at a time. Our experiments with memcached, however, leveraged code developed for the Hodor project [18], which allows a data structure to be shared safely among mutually untrusting applications, with independent failure modes. We speculate that such structures may provide a particularly attractive alternative to files for shared abstractions in a future filled with nonvolatile main memory.

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