Linearizability of Persistent Memory Objects

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Fast Nonvolatile Memory

- NVM is on its way
  - PCM, STT-MRAM, memristors, ...
- Tempting to put some long-lived data directly in NVM, rather than the file system

- But registers and caches are likely to remain transient, at least on many machines
- Have do we make sure what we get in the wake of a crash is consistent?

Problem: Early Writebacks

- Could assume HW tracks dependences and forces out earlier stuff
  - [Condit et al., Pelley et al., Joshi et al.]
- But real HW not doing that any time soon; have to explicitly force things out in order
  - ARM, Intel ISAs
- Buffering?
  - Can be done in SW now, with shadow memory
  - Likely to be supported in HW eventually

Outline

- Theory review — linearizability of (transient) concurrent object histories
- Extension of theory to persistence — *durable linearizability*
- *Explicit epoch persistency* at the hardware level
  - to explain the behavior of implementations
- Automatic transform to convert a (correct) transient nonblocking object into a (correct) persistent one
- Methodology to prove safety for more general objects
- Future directions

Theory Review

- Focus on *objects* that we can put in libraries
  - data abstractions defined in terms of API (methods)
  - stack, queue, deque, set, mapping, priority queue, …
- Many possible implementations (data structures)
  - Correctness = *safety* + *liveness*
  - Focus on safety in today's talk
    (DISC paper also looks at liveness)

Object Histories

- Interleavings of operations (method invocations) performed by a set of threads
  - Concrete history: all the instructions
  - Abstract history: invocations and responses only (calls & returns)

I • • I • R • • • I I R • • R I • • I R • R •

- *Sequential* = every invocation followed immediately by its response
- *Well formed* = every *thread subhistory* is sequential

Safety

- Implementations generate concrete histories
- Implementation is *safe* if every realizable (single-object) concrete history corresponds to a (well-formed) safe abstract history
- Safe abstract history = *linearizable* (next slide)
- Object semantics defined as a set of abstract sequential histories
  - e.g., a queue is an object with enqueue & dequeue methods, where the *n*th dequeue yields the value passed to the *n*th enqueue, if there has been one, else $\perp$

Linearizability [Herlihy & Wing 1987]

- Standard safety criterion for transient objects
- History H is safe if well-formed and equivalent (same invocations and responses, inc. args) to some sequential history S that respects
  1. object semantics (*legal*)
  2. “real-time” order (res(A) $<_H$ inv(B) $\Rightarrow$ A $<_S$ B)
     (subsumes per-thread program order)
- Programs, of course, generate *multi-object* concrete histories
- Linearizability is nice because it's a *local* property: safety of individual objects implies safety of multi-object programs
  - Follows from respect of real-time order
- Need an extension for persistence

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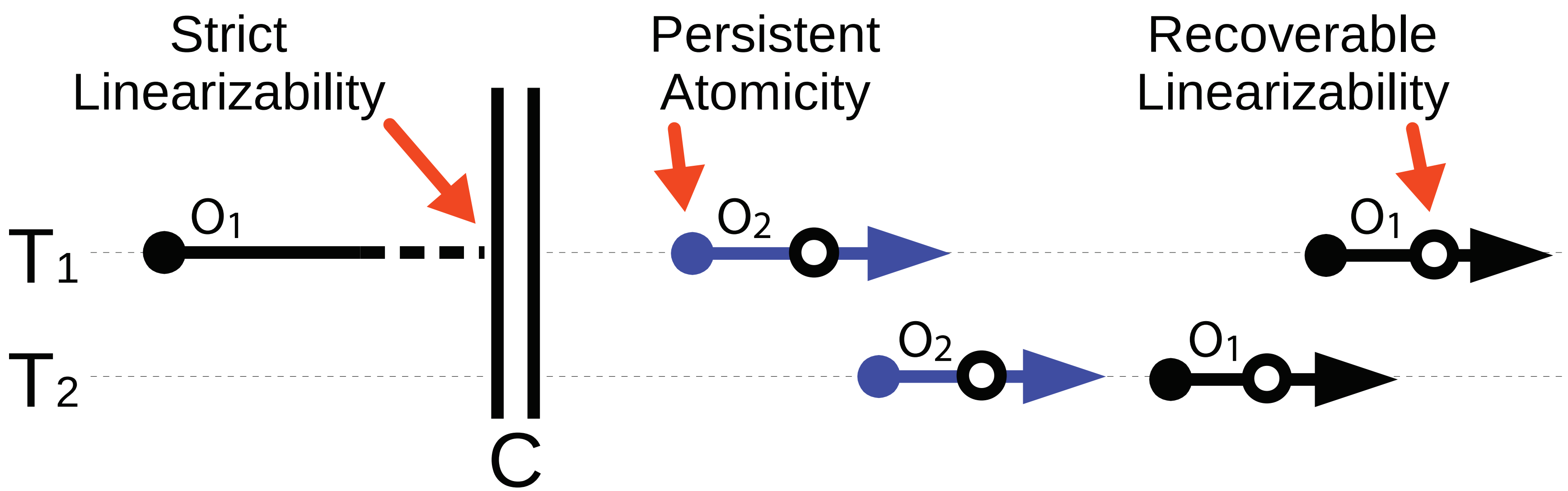
Prior Work on Persistency

- *Strict linearizability* [Aguilera and Frølund 2003]
  - At a crash, every pending operation has happened or it hasn't
  - Too restrictive — can't leave anything hanging (e.g., announce array)
- *Persistent atomicity (linearizability)* [Guerraoui et al. 2004]
  - Every pending operation happens before its thread invokes anything post-crash
  - Gives up on locality — have to reason across objects
- *Recoverable linearizability* [Berryhill et al. 2015]
  - Every pending operation happens before its thread invokes anything *on the same object* post-crash
  - Gives up on program order around a crash — thread can perform an op on some other object before "coming back to" the pending op

Comparing These Conditions

- Where must T_1's pending op linearize?



- Persistent and Recoverable Linearizability are the same if threads don't survive a crash — and they don't in real life!
- We use *Recoverable Linearizability* for the merged condition, under a full-system–crash failure model

Durable Linearizability

- (Abstract) history H is *durably linearizable* iff
  1. it's well formed (no thread survives a crash) and
  2. ops(H) is linearizable (elide the crashes)
- But that requires every op to persist before returning
- Want a *buffered* variant
- Say A "happens before" B (A $\prec$ B) in an abstract history H if A.res precedes B.inv in H
- A $\prec$-*consistent cut* of a crash-free history H is a prefix P of H such that if V $\in$ P and V' $\prec$ V in H, then V' $\in$ P, with V' $\prec$ V in P.

Buffering

- (Abstract) history H is *buffered durably linearizable* iff for each *era* E_i we can identify a $\lessdot$-consistent cut P_i such that $P_0 \ldots P_{i-1} E_i$ is linearizable $\forall\, 0 \leq i \leq c$, where c is the number of crashes.
  - That is, we may lose something at each crash, but what's left makes sense. (Again, buffering may be in HW or in SW.)
- NB: Because actual persistence is delayed, and must be controlled across objects, buffered durable linearizability is not a local property.

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Memory Model Background

- Sequential consistency: memory acts as if there was a total order on all loads and stores across all threads
  - » Conceptually appealing, but only IBM z still supports it
- Relaxed models: separate *ordinary* and *synchronizing* accesses
  - » Latter determine cross-thread ordering arcs
  - » *Happens-before order* derived from program order and synchronizes-with
- Release consistency (ARM v8): each store-release synchronizes with the following load-acquire of the same location
  - » Each local access happens after each previous load-acquire and before each subsequent store-release in its thread
- But none of this addresses persistence

Persistence Instructions

- Explicit write back (“pwb”); persistence fence (“pfence”); persistence sync (“psync”)
- We assume E1 $\lessdot$ E2 if
  - » they're in the same thread and
    - – E1 = pwb & E2 $\in$ {pfence, psync}
    - – E1 $\in$ {pfence, psync} and E2 $\in$ {pwb, st, st_rel}
    - – E1, E2 $\in$ {st, st_rel, pwb} and access the same location
    - – E1 $\in$ {ld, ld_acq}, E2 = pwb, and access the same location
    - – E1 = ld_acq and E2 $\in$ {pfence, psync}
  - » they’re in different threads and
    - – E1 = st_rel, E2 = ld_acq, and E1 synchronizes with E2

Concrete Histories

- H is well-formed iff
  - abstract(H) is well-formed
  - all instructions are between inv. and res. (or crash or end)
  - loaded values respect the *reads-see-writes* relation
    - return a most recent or unordered store under happens-before
- NB: Implementations (programs) give us *sets* of possible histories — possible interleavings.
- A history is *data-race–free* if conflicting accesses are never adjacent; an implementation is DRF if *all* of its realizable histories are DRF.

Extensions for Persistence

- H is well-formed iff all previous requirements *and*
  - for each variable x, at most one store is labeled “persisted” in each era
  - no unpersisted store of x between the persisted store of x and (1) a psync or (2) the persisted store of any other location y
- NB: reads-see-writes augmented to allow returning the persisted store of the previous era in the wake of a crash
- Key problem: you see a write, act on it, and persist what you did, but the original write doesn't persist before we crash.

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Persistence Transform

- st → st; pwb
  st_rel → pfence; st_rel; pwb
  ld_acq → ld_acq; pwb; pfence
  cas → pfence; cas; pwb; pfence
  ld → ld
- Can prove: if the original code is DRF and linearizable, the transformed code is durably linearizable.
  - Key is the ld_acq rule
- But: not all stores *have* to be persisted
  - elimination/combining, announce arrays for wait freedom
- How do we build a correctness argument for more general, hand-written code?

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Linearization Points

- Every operation “appears to happen” at some individual instruction, somewhere between its call and return.
- Proofs commonly leverage this formulation
  - In lock-based code, could be pretty much anywhere
  - In simple nonblocking operations, often at a distinguished CAS
- In general, linearization points
  - may be statically known
  - may be determined by each operation dynamically
  - may be reasoned in retrospect to have happened
  - (may be executed by another thread!)

Persist Points

- Proof-writing strategy (again, challenge is make sure nothing new persists before something old on which it depends)
- Implementation is (buffered) durably linearizable if
    1. somewhere between linearization point and response, all stores needed to "capture" the operation have been pwb-ed and pfence-d;
    2. whenever M1 & M2 overlap, linearization points can be chosen s.t. either M1's persist point precedes M2's linearization point, or M2's linearization point precedes M1's linearization point.
- NB: nonblocking persistent objects need helping: if an op has linearized but not yet persisted, its successor in linearization order must be prepared to push it through to persistence.

Objects from the Literature

- Many strictly linearizable
  - trees [Chen & Jin, VLDB'15; Venkataraman et al., FAST'11; Yang et al., FAST'15]
  - hash maps [Schwalb et al., IMDM'15]
  - file system metadata [Condit et al., SOSP'09]
- Also a few buffered strictly linearizable [Moraru et al., TRIOS'13]
- And a few durably (but not strictly) linearizable
  - JustDo Logging [Izraelevitz et al., ASPLOS'16]
  - Hope to see more!

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Ongoing Work

- More optimized, nonblocking persistent objects
- Integrity in the face of buggy (Byzantine) user threads
  - File system no longer protects metadata!
- Integration w/ transactions

- Suggestions welcome!

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Liveness

- *Nonblocking sync* — bounded # of own steps
- *Bounded completion* — in the wake of a crash, for each operation m that was pending on object O, ∃ k s.t. if some post-crash era has at least k instructions executed in O, m has completed or it never will.