Understanding and Optimizing Persistent Memory Allocation

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Challenges

Resizable durable data structures on nonvolatile memory require an allocator that manages the persistent memory region. However, this poses additional challenges compared to transient allocators:

1. Consistency of allocator's metadata after a crash (**failure atomicity**).
2. **Memory leaks** due to failures between allocation and attachment, or between detachment and deallocation:

```
Node* t = list->tail();
t->next = malloc(sz); // sz == sizeof(Node)
          ↑
        Crash
```

3. **Pointer** reusability across executions.

Failure-induced Memory Leaks

State-of-the-art persistent allocators typically rely on one of two strategies to handle failure-induced memory leaks:

1. Failure-atomic **malloc-to** and **free-from** operations, which effectively makes (de-)allocations *durably linearizable* (and thus expensive).

```
t->next = malloc(sz) ⟹ malloc_to(t->next, sz)
```

2. Traditional malloc and free, with offline tracing *garbage collection* (GC) from *persistent roots*.

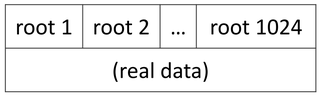

Figure 1. Example of a Memory Region

Recoverability

An allocator is **recoverable** if, in the wake of a crash, it is able to bring its metadata to a state in which all and only the *"in use" blocks* are allocated. In use blocks are defined as those that are:

- Malloc-to-ed but not yet free-from-ed, or
- Reachable from persistent roots via tracing.

Observation: Given a proper tracing mechanism, almost any transient allocator can be made recoverable by identifying the in-use blocks during recovery and reconstructing the allocator's transient metadata.

Allocator methods must also be failure-atomic, either via logging or by adding appropriate flushes and fences to nonblocking code.

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Ralloc

Ralloc is the first nonblocking, recoverable allocator.[¤] Based on the (transient) LRMalloc,[1] it retains the traditional malloc/free interface and adds three key innovations:

1. **Minimum run-time overhead** by persisting just enough information to permit GC and metadata reconstruction after a crash.
2. **Filter functions** to avoid false positives in conservative GC for type-unsafe languages (e.g., C++). These enumerate internal pointers for a given type of block:

```
class TreeNode
{
   … // content fields
   TreeNode* left, *right;
}
```

```
void filter(TreeNode* ptr)
{
   visit(ptr->left);
   visit(ptr->right);
}
```

3. **Position-independent pointers** to allow persistent memory regions to be mapped at an arbitrary address.

[¤] Source code available at https://github.com/qtcwt/ralloc

Comparison to State of the Art

	PMDK[2]	Makalu[3]	Ralloc
Memory Leaks	malloc-to & free-from	malloc & free w/ Conservative GC	**malloc & free** w/ Conservative GC & Optional **Filter Function**
Atomicity	Logging	Undo Logging	**Reconstruction**
Pointers	Position Independent ID + Offset (128 bits)	Fixed Mapping Address	**Position Independent** *Off-holder** (**64 bits**)
Liveness	Lock-based	Lock-based	**Lock-free**

*An *off-holder*[4] holds the offset to the target *from the pointer itself.*

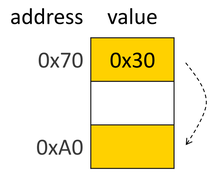
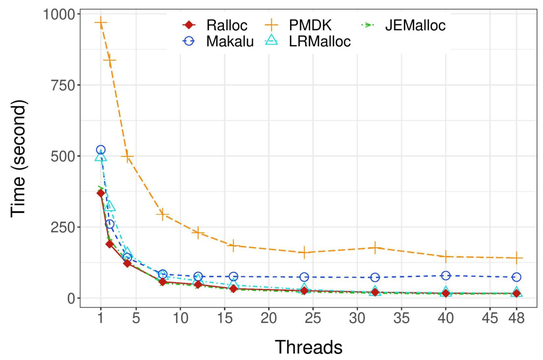


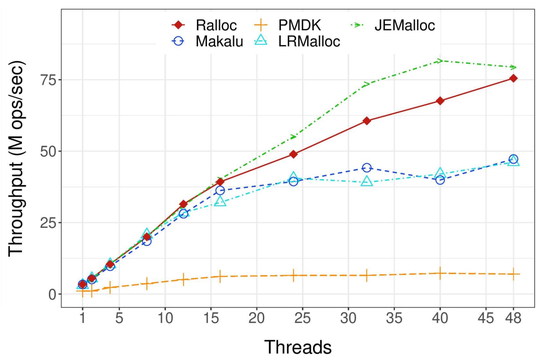
Figure 2. Example of Off-holders

Experiments

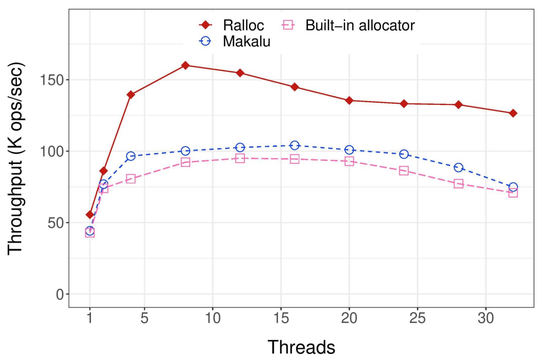
Environment: Two Intel Xeon Silver 4114 CPUs (total of 20 physical cores / 40 hyper-threads) and emulated persistent memory on DRAM.



(a) Threadtest[5] (lower is better)



(b) Larson[5] (higher is better)



(c) Memcached[6] (higher is better)

References

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[2] A. Rudoff and M. Slusarz. Persistent memory development kit, Sept. 2014. http://pmem.io/pmdk/.
[3] K. Bhandari, D. R. Chakrabarti, and H.-J. Boehm. Makalu: Fast recoverable allocation of non-volatile memory. In OOPSLA, Amsterdam, The Netherlands, Oct. 2016.
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[6] S. Nalli, S. Haria, M. D. Hill, M. M. Swift, H. Volos, and K. Keeton. An analysis of persistent memory use with WHISPER. In ASPLOS, Xi'an, China, 2017.