Metall: An Allocator for Persistent Memory

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Background

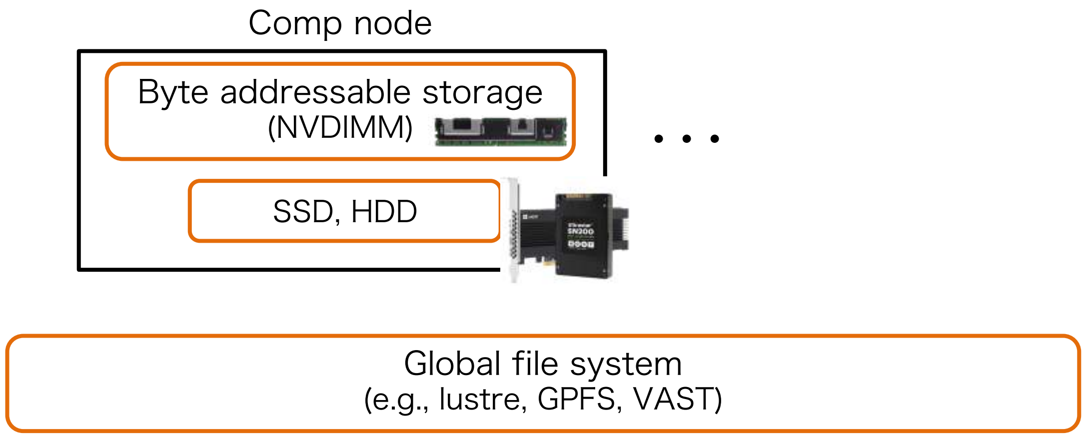
Large-scale Data Analytics

- High volume data analytics is one of key challenges in exascale
- Data ingestion
  - Indexing and partitioning data with analytics-specific data structures
    - e.g., read raw graph data from text files, and transform into a graph data structure
  - Often more expensive than analytics
  - The same data (or derived data) is re-ingested frequently
    - e.g., run multiple analytics to the same data, test different parameters, develop/debug analytics program

Background

Persistent Memory (PM) in HPC

- Substantial performance improvements and cost reductions
- Many HPC systems have PM devices to leverage them in large data processing with reduced cost and power consumption



Supercomputers w/ PM

- Sierra
- Summit
- Aurora
- Mammoth
- Fugaku (RIKEN, Japan)

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Once constructed, data structures can be re-analyzed and updated beyond a single process lifecycle

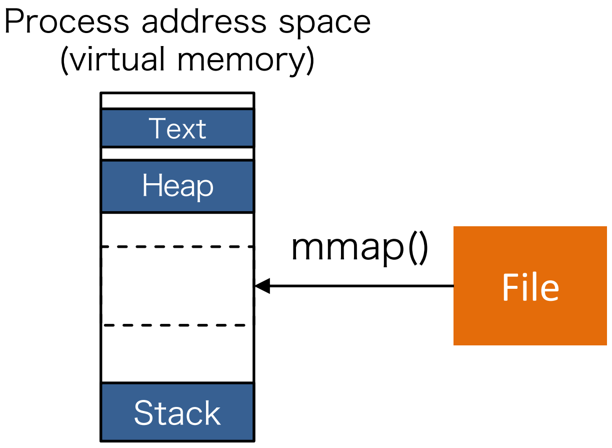
Background
Data Serialization

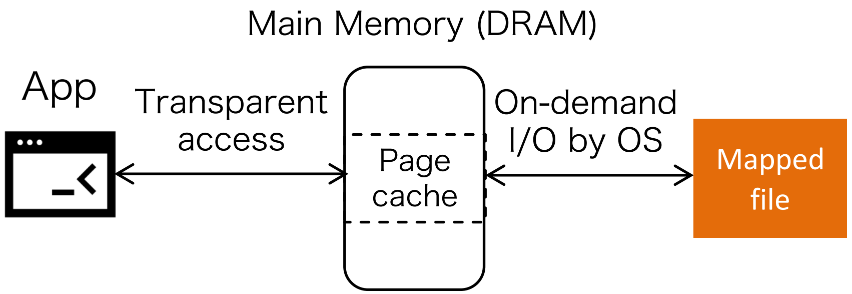
- Data serialization is expensive
  - Dismantling and assembling complex data structures are expensive in terms of performance and programming cost

- Can we allocate data into PM directly and store the data as is while providing transparent accesses to applications?

Background
Memory-mapped File Mechanism (mmap() system call)

- Maps a file into a process's virtual memory (VM) space
- Applications can access mapping area as if it were regular memory
- *Demand paging*
  - OS performs I/O on-demand by *page* granularity (e.g., 4 KB or 64 KB)
  - OS keeps cache in DRAM (*page cache*)
- Can map a file bigger than the DRAM capacity
- Existing PM devices accessed via mountable filesystems (e.g., "/ssd/")





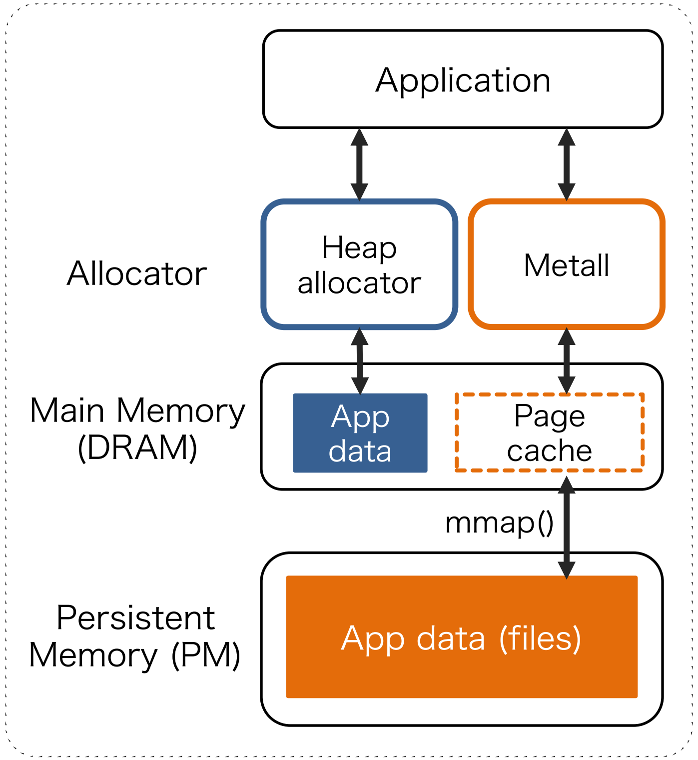
mmap is powerful; however,
calling mmap for every memory allocation is expensive

Metall[Iwabuchi'19]
A C++ Allocator for Persistent Memory

Fork me on GitHub

[github.com/LLNL/metall]

- A memory allocator built on top of a memory mapping region
- Enables applications to allocate heap-based objects into PM, just like main-memory
- Can resume memory allocation work after restarting
- Incorporates state-of-the-art allocation algorithms
  - Some key ideas from SuperMalloc[Kuszmaul'15] and jemalloc
- Employs the API developed by Boost.Interprocess (BIP)
  - Useful for allocating C++ custom data structures in PM



Persistent Memory Allocation using Metall

Create new data (create.cpp)

```
void main () {
metall::manager metall_mgr(metall::create_only, "/ssd/test");
int* n = metall_mgr.construct<int>("val0")();
*n = 10;
}
```

Allocate a manager object

Directory to store data

Allocate and construct an object

Store a key to retrieve the data later

Metall::manager's destructor synchronies data with the PM (files)

Reattach the data (open.cpp)

```
void main () {
metall::manager metall_mgr(metall::open_only, "/ssd/test");
int* n = metall_mgr.find<int>("val0").first;
std::cout << *n << std::endl;
}
```

Retrieve data with its key

Terminal

```
$ ./create
$ ./open
10
```

Data is directly accessed in PM
(no serialization overhead)

Metall with C++ Standard Template Library (STL) Container

A vector type with the STL allocator in Metall

```
using vec_t = vector<int, metall::allocator<int>>;
```

Template parameters of the STL vector container

```
template<
    class T,
    class Allocator = std::allocator<T>
> class vector;
```

Create new data (create.cpp)

```
void main () {
metall::manager metall_mgr(metall::create_only, "/ssd/test");
vec_t* pvec = metall_mgr.construct<vec_t>("vec")(metall_mgr.get_allocator());
pvec->push_back(10);
}
```

← Can use it normally, including changing its capacity

↑ Arguments to vec_t's constructor

Reattach the data (open.cpp)

```
void main () {
metall::manager metall_mgr(metall::open_only, "/ssd/test");
auto pvec = metall_mgr.find<vec_t>("vec").first;
pvec->push_back(20);
}
```

← Can resume work, including changing its capacity

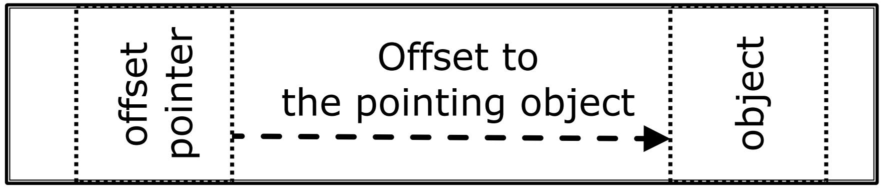
Metall follows the C++ standard style of using custom allocator
(no directives, no change to compilers)

Solutions To Random Memory Placement

- Raw pointers
  - Must be replaced with *offset pointers*

```
struct offset_pointer {
    int64_t offset;
}
```

Address Space



* The concept of non-raw pointer is already integrated in C++

- References, virtual function, and virtual base class
  - Must be removed since raw pointers are used
- STL Containers
  - Some implementations do not support offset pointers fully
    - e.g., std::list (also std::deque?) in libstdc++ (GCC)

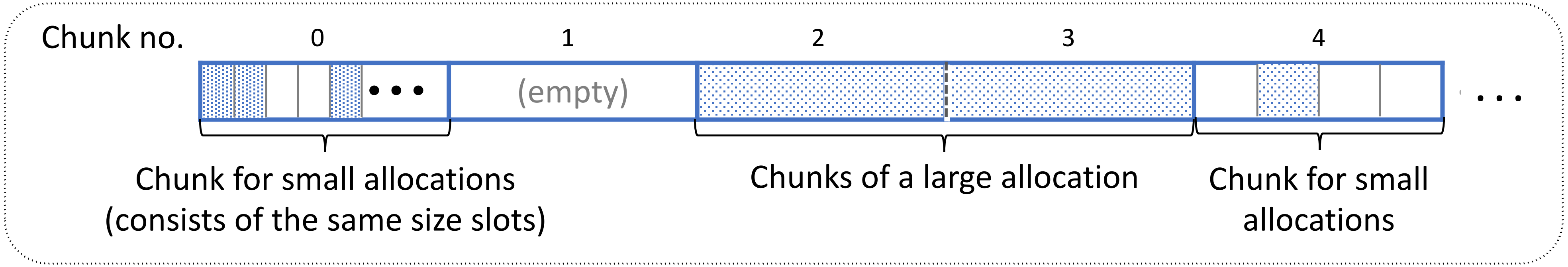
Metall Internal Architecture

Key design philosophy

- *Virtual memory is cheap in 64-bit machine, physical memory is dear* [Kuszmaul'15]
- Leverage *demand paging* (physical memory is not consumed until accessed)

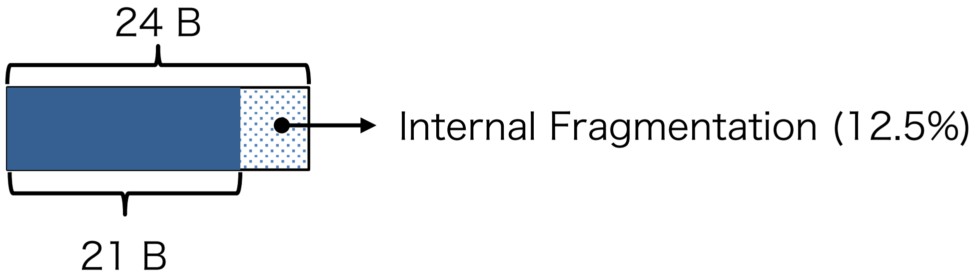
-> Simplifies implementation & increases speed

- Application heap segment
  - Reserves a large continuous VM region in the process's address space
  - Maps backing files to the VM region on demand
    - Efficiently uses PM space and improve I/O performance



Metall Internal Architecture
Allocation Size

- Small size category (e.g., <= 1 MB)
  - Rounded up to the nearest internal allocation size
  - Internal sizes are designed to keep internal fragmentations < 25%[Supermalloc][jemalloc]

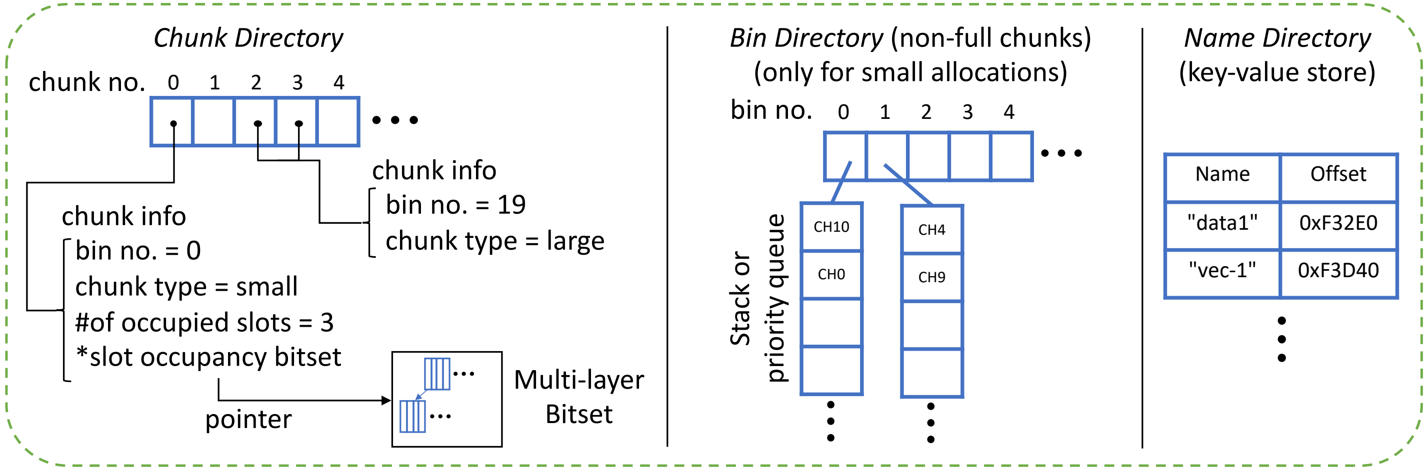


- Large size category (e.g., > 1 MB)
  - Rounded up to the nearest power of 2
  - Designed not to waste physical memory much
    - <u>uncommitted</u> (non-touched) page does not consume physical memory
    - Worst cases:
      - 1.6% when allocating 1MB + 1 B with 4 KB page
      - 6.3% when allocating 1MB + 1 B with 64 KB page

Metall Internal Architecture
Memory Allocation Management Data (SLUB allocator)

- Allocated in DRAM, separating from application heap segment to improve data locality
  - Unserialized/serialized when Metall's constructor/destructor is called

Management Data (constructed in **DRAM**)



Name	Offset
"data1"	0xF32E0
"vec-1"	0xF3D40

- Employs state-of-the-art allocation algorithms

- Free-slot caches
  - CPU core and CPU socket level to improve multi-thread performance

Snapshot/versioning in Metall

- Metall employs coarse-grained ('snapshot') persistence policy

```
metall::manger manager(...); // mmap()
// Application does some work:
// memory allocations and write operations
manager.~metall::manager(); // msync() and munmap()
```

→ Data is consistent

Data is inconsistent

→ Data is consistent

  - snapshot() creates a snapshot

```
metall::manger manager(...);
// Application does some work
manager.snapshot('/mnt/ssd2/data');
// Application does some work
manager.~metall::manager();
```

→ calls msync() and copies the mapped files to the '`/mnt/ssd/data`'
'`/mnt/ssd/data`' is consistent if snapshot() finishes correctly

How to implement a lightweight snapshot?

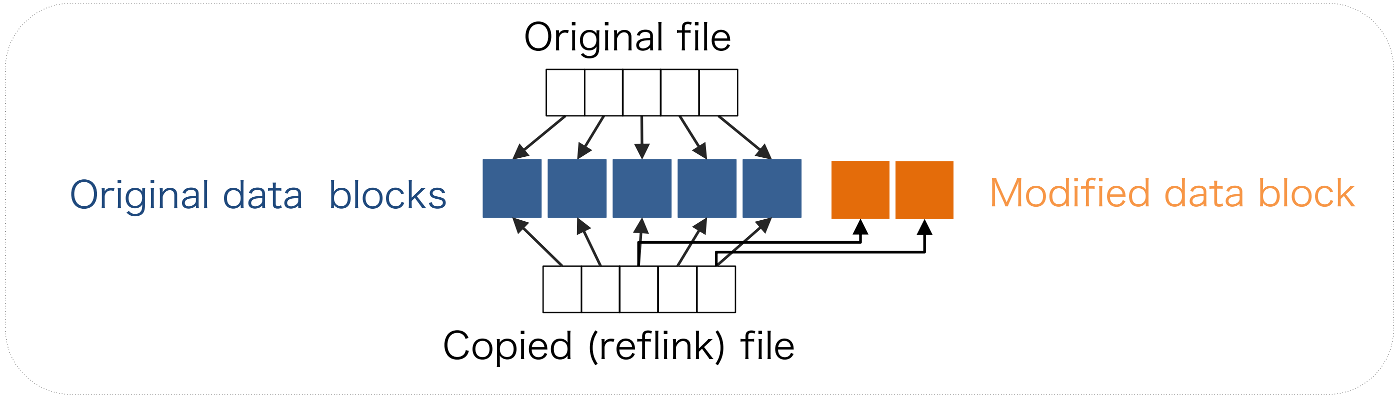
Persistence Policy — fine grained vs coarse grained

- Fine grained persistence policy
  - Synch data with persistent memory after every write operation
  - Ideal for transactional operations with recent byte-addressable PM
  - Can incur an unnecessary overhead for non-transactional apps

- Coarse grained persistence policy
  - Metall employs 'snapshot' consistency
  - A snapshot is created when the destructor or a snapshot method is invoked
  - Could cause data inconsistency if there is a clash before 'snapshot'

Lightweight Snapshot/versioning in Metall

- Calls msync() and copies backing-files to another location using *reflink*
- reflink
  - copy-on-write file copy mechanism implemented in filesystems (e.g., XFS, ZFS, Btrfs)



  - In case reflink is not supported by the filesystem, Metall automatically falls back to a regular copy

**Lightweight snapshot is useful for many situations:
e.g., incremental data processing and crash consistency (node failure, application bugs)**

Evaluation

1. Dynamic graph construction
   (key-value store bench with skewed data)
   - Shared-memory allocation intensive workload
   - Insert edges with multiple threads
   - Workloads
     1. Construct a graph in PM
     2. Construct a graph in PM, taking snapshots
     3. Uses a user-level mmap implementation (Umap)

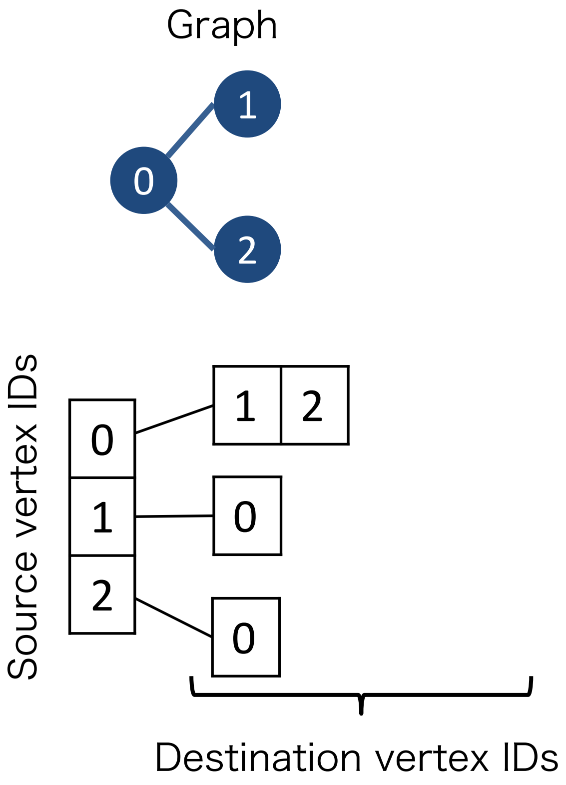
Evaluate memory allocation and snapshot performance

2. miniVite + Metall
   - miniVite
     - ECP application (ExaGraph project)
     - Graph community detection

Demonstrate the impact of Metall with a real graph application

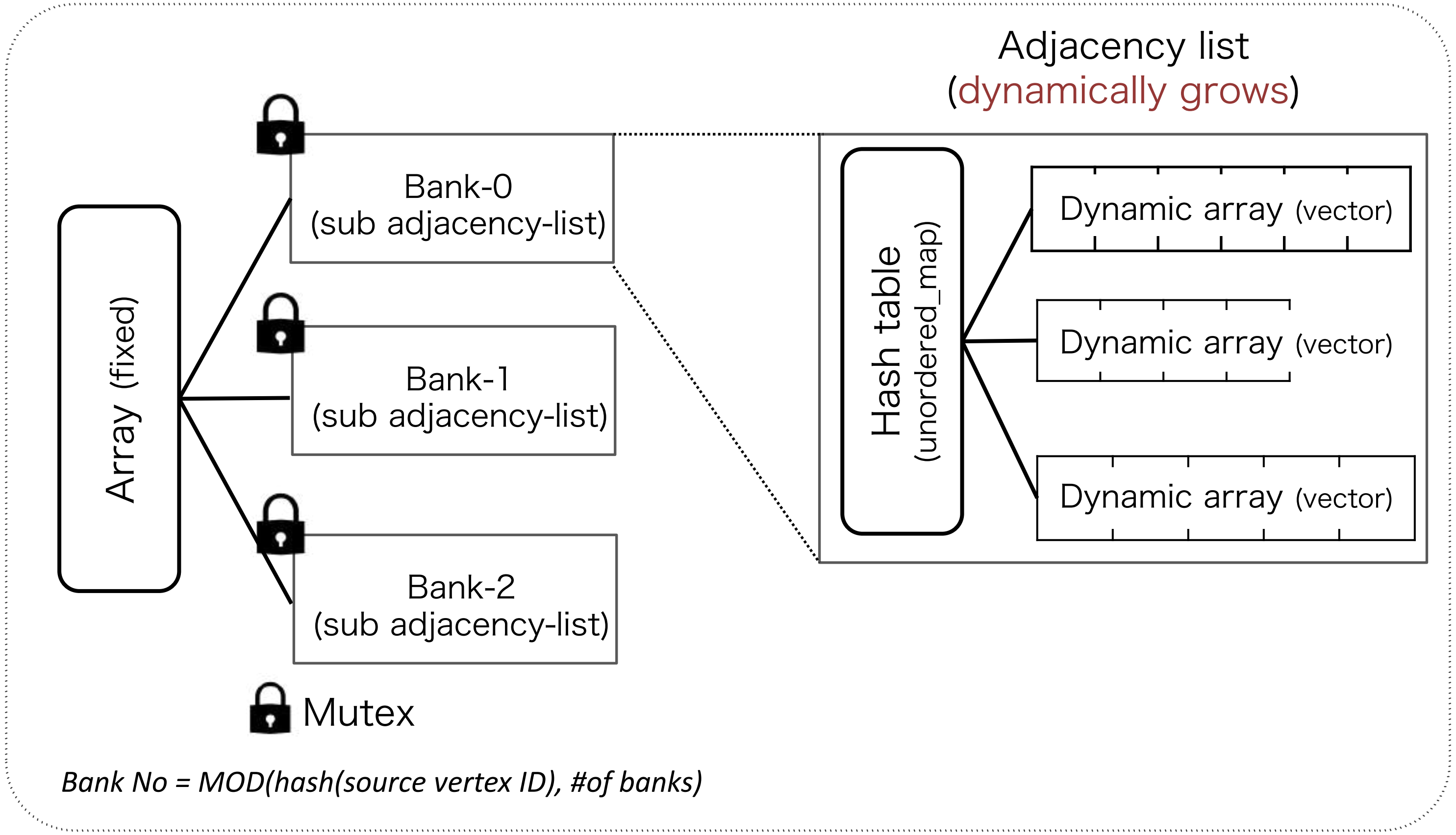
Evaluation
Graph Data Structure

- Adjacency list (one of de-facto standard graph data structures)



Vertex ID is a 64-bit int

Multi-banked adjacency list



Bank No = MOD(hash(source vertex ID), #of banks)

Evaluation

Machine Configuration

- Used two **single-node** machines at LLNL

EPYC (conventional PM device)

Storage	NVMe SSD
DRAM	256 GB
CPU	AMD EPYC CPU x 2 (96 threads)

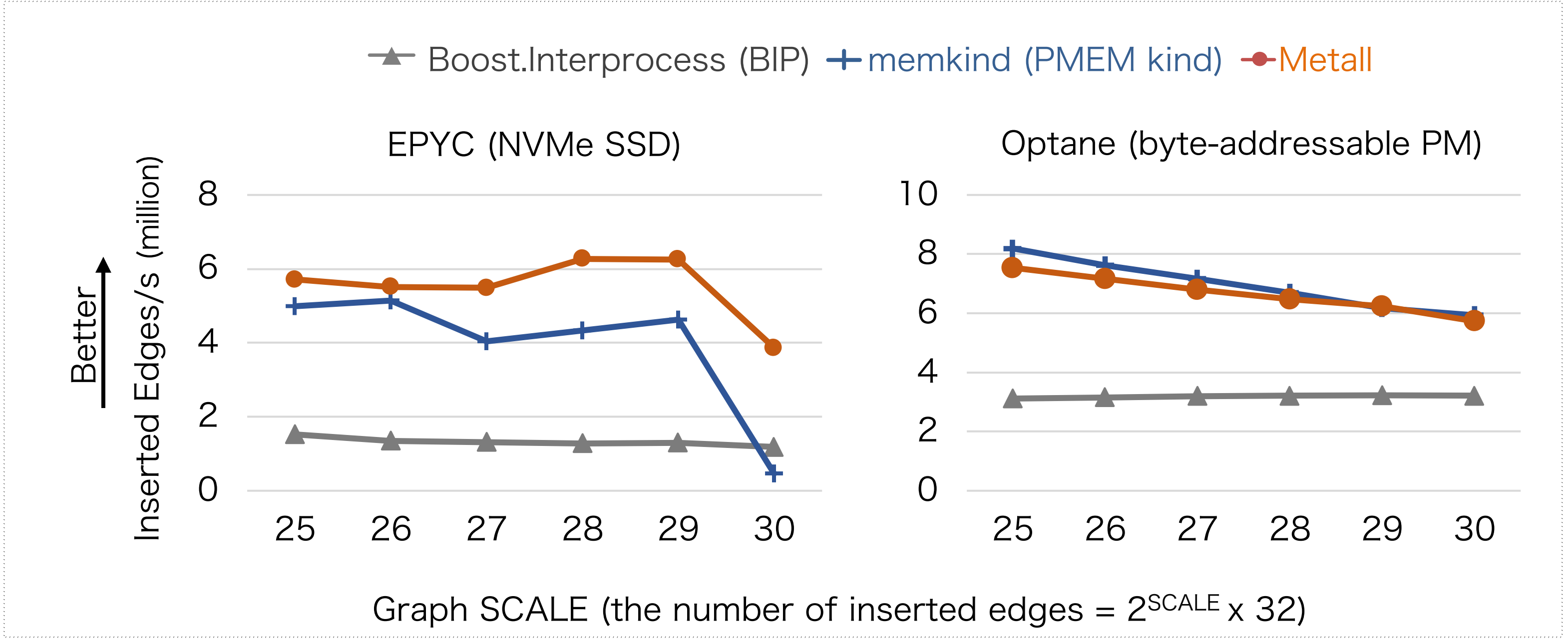
Optane (byte addressable PM device)

Storage	Intel Optane DC Persistent Memory (App Direct Mode + DAX)
DRAM	192 GB
CPU	Intel Skylake x 2 (96 threads)

Evaluation Result
Dynamic Graph Construction

shared-memory
multi-thread

- Baselines (memory allocators that use file-backed mmap underneath)
  - Boost.Interprocess
    - Uses a single tree structure for memory allocation management
  - memkind (PMEM kind)
    - Provides an allocator built on top of *jemalloc*
    - Cannot reattach data (uses PM as extended memory)



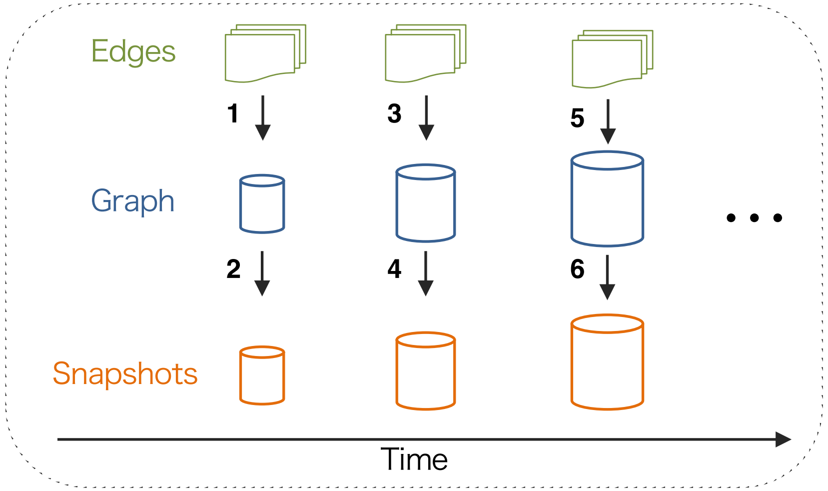
(SCALE 30 is larger than DRAM)

Metall provides persistent memory features whereas PMEM kind does not.

Evaluation Result

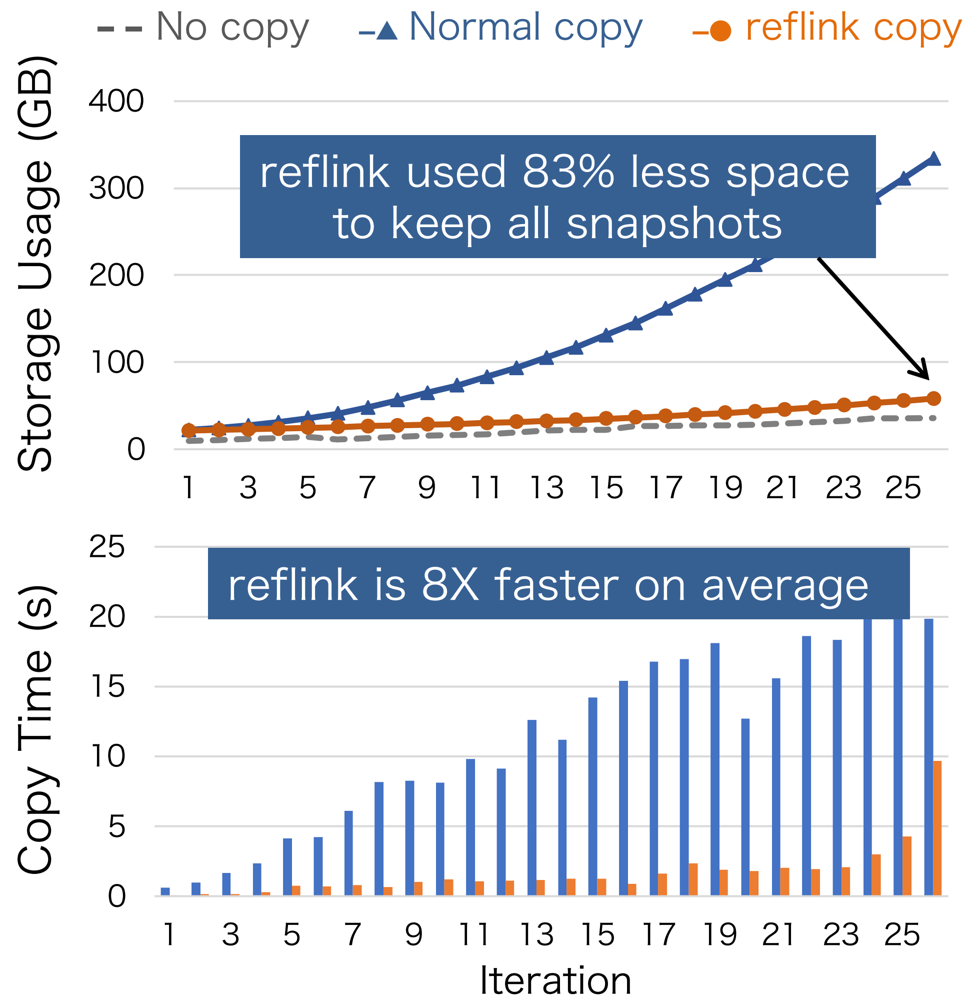
Incremental Graph Construction, Taking Snapshots

- Workload
  - Take a snapshot after inserting each chunk (64M edges)
  - Insert edges into the original graph



- Dataset
  - Wikipedia page link insertions (1.8B edges)
    (curated by parsing English Wikipedia's revision history)
- Machine
  - EPYC machine (NVMe SSD with XFS filesystem)

*reflink: copy-on-write file copy



reflink used 83% less space to keep all snapshots

reflink is 8X faster on average

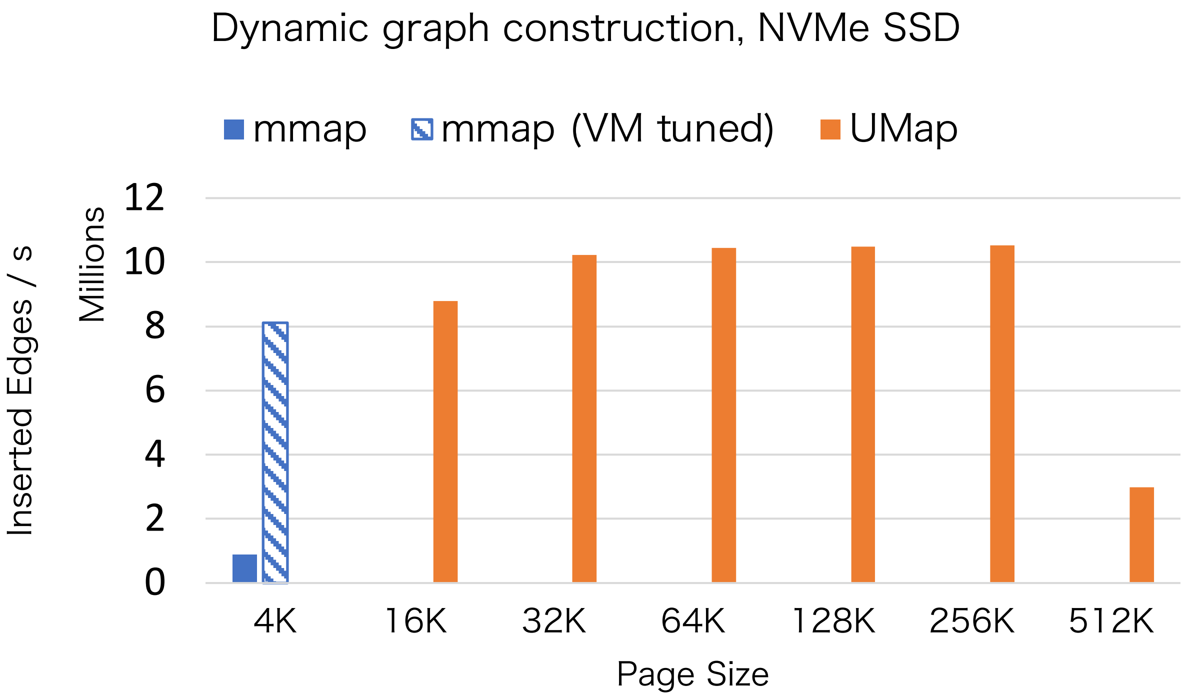
Evaluation Result

Metall + Umap

Work with Karim Youssef
(mentored student intern)

SC20 poster to appear

- Metall can leverage another ECP system software
- Umap[Peng'18]
  - User-level mmap implementation in ECP (PI: Gokhale)
  - Page size (≒I/O size) and page buffer size are configurable from application


Dynamic graph construction, NVMe SSD

Configurations (all use Metall)

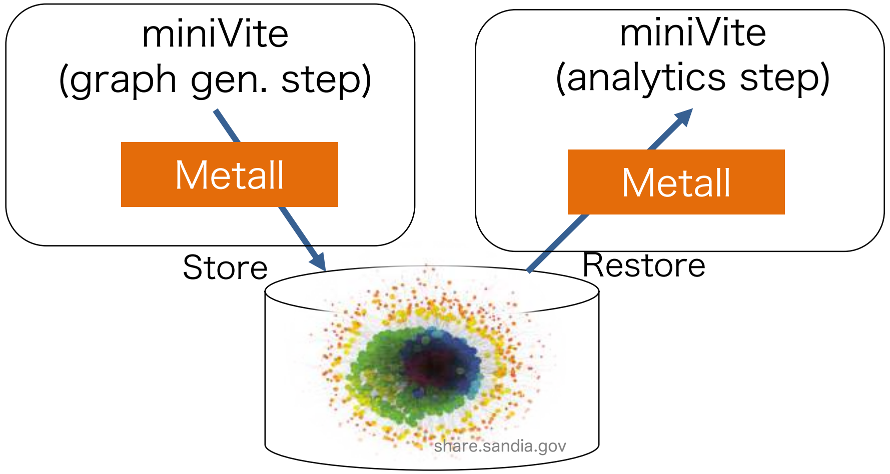
- mmap
  - system mmap + Metall
- mmap (VM tuned)
  - system mmap + Metall
  - Tuned page cache behaviors
  - Required privileged access
  - System-wide change
- Umap
  - Umap + Metall

Evaluation Result
miniVite + Metall

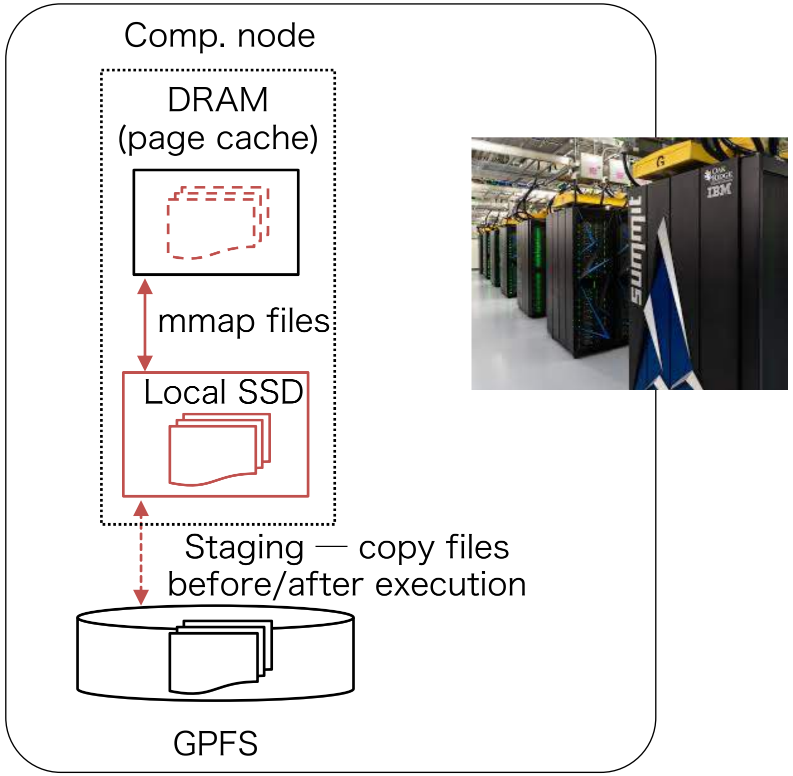
Collaboration with ECP ExaGraph@PNNL

SC20 poster to appear

- miniVite[Ghosh'18]
  - ECP proxy application suite
  - Distributed graph community detection app
  - Graph generation takes up to 20X than the analytics
  - Uses 3 vector containers to hold graph data
- miniVite + Metall
  - Store and reuse a graph object using Metall



Evaluation System
(OLCF/ORNL Summit)

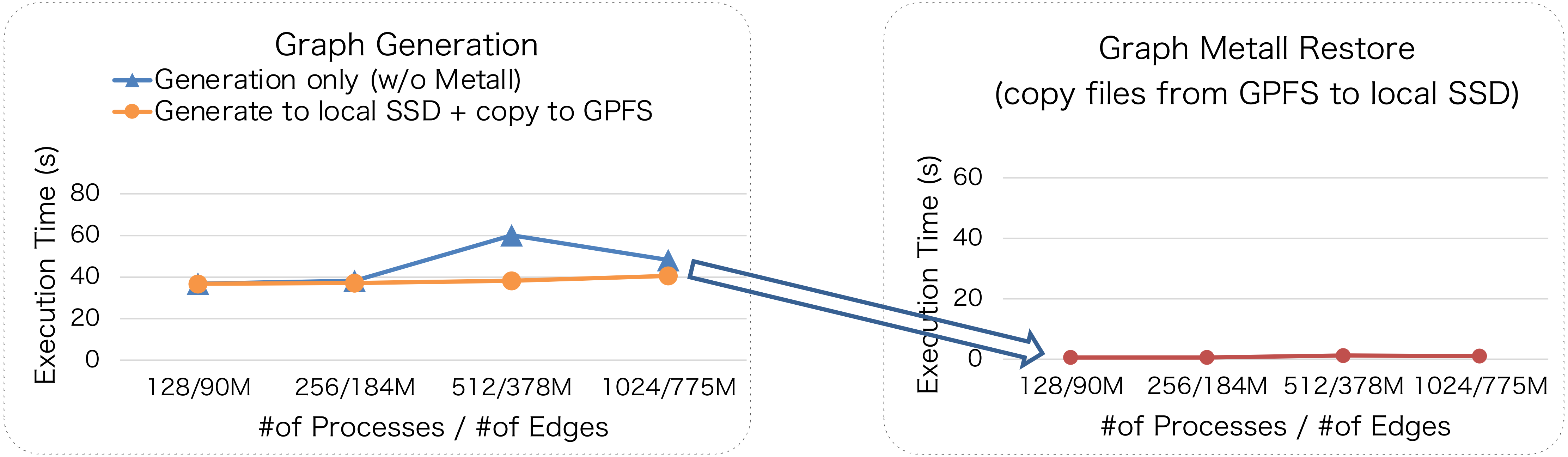


miniVite + Metall

SC20 poster to appear

OLCF/ORNL Summit

(community detection step took 1.2 - 1.8 s)



Low overhead to store graph

generation time >> Metall restore time

Related Work

- Heap allocators (e.g., jemalloc, tcmalloc, malloc implementations)
  - Many studies have been conducted and showed notable results
  - Cannot persistently store their internal structures
- NVMalloc
  - Allocates memory on a distributed non-volatile memory (NVM) storage system
  - Creates a file per memory allocation request
- libpmemobj (in PMDK)
  - Employs a fine-grained persistence policy (ideal for transactional operations)
  - Requires fine-grained cache-line flushes to the persistent media
- Boost.Interprocess
  - Designed for interprocess communication (not desingned as a persistent memory)
  - Employs a single tree structure to govern memory allocation

Metall is the first general purpose high performance persistent memory allocator

Summary of Metall

- Key features
  - Enables applications to allocate heap-based objects into PM, just like main-memory
  - Rich API for custom C++ data structures
  - State-of-the-art allocation algorithms
  - Efficient snapshost using *reflink*

- Open source
  - Available at github.com/LLNL/metall
  - Full documentation is hosted on Read the Docs
  - Travis CI and GitLab CI (in LC) are set up

- Collaborations
  - ECP: Umap and ExaGraph (miniVite)
  - GraphBLAS (Scot McMillan @ CMU-SEI)
  - HavoqGT (distributed graph processing framework at LLNL)
  - LDRD-ER FY21 (R. Pearce, Interactive Exploratory Graph-Enabled Data Analytics at HPC Scales)

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