Metall:
A Persistent Memory Allocator For Data-Centric Analytics

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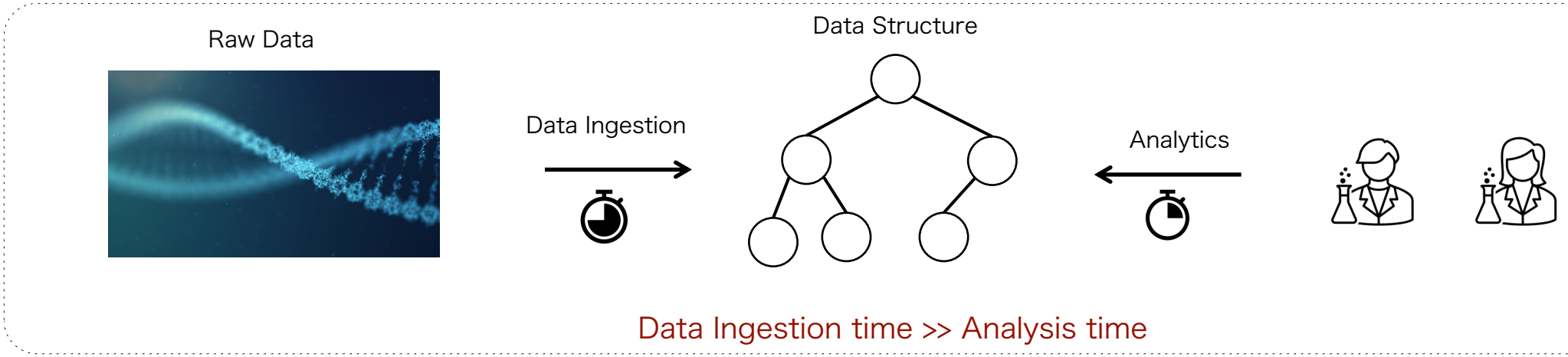
Background
Large-scale Data Analytics

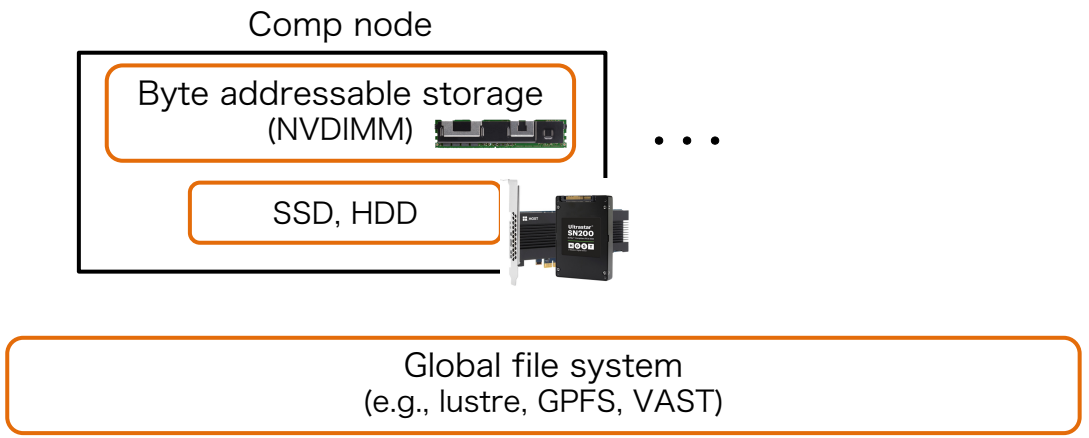
- High volume data analytics is one of the key challenges in exascale
- Data ingestion
  - Indexing and partitioning data with analytics-specific data structures
    - e.g., read raw graph data from text files, and transform into a graph data structure
  - Often more expensive than analytics
  - The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



Background

Persistent Memory (PM) in HPC

- Substantial performance improvements and cost reductions in non-volatile random-access memory (NVRAM)
- Many HPC systems have various types of NVRAM devices today



Supercomputers w/ PM

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

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These devices offer cost-effective ways of persistently storing large datasets with efficient means of accessing the data for processing

Background

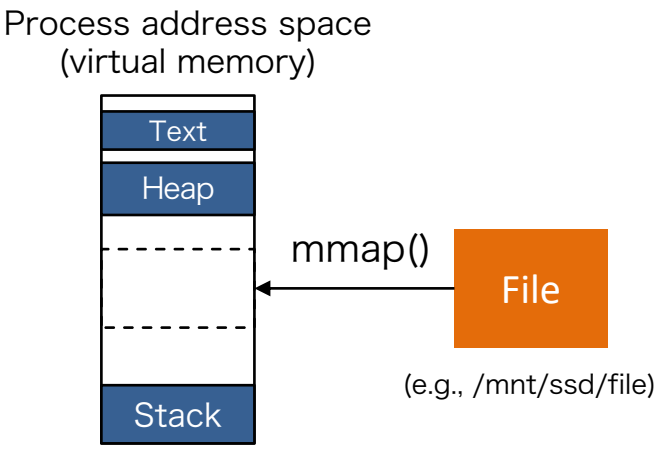
Store Data into PM

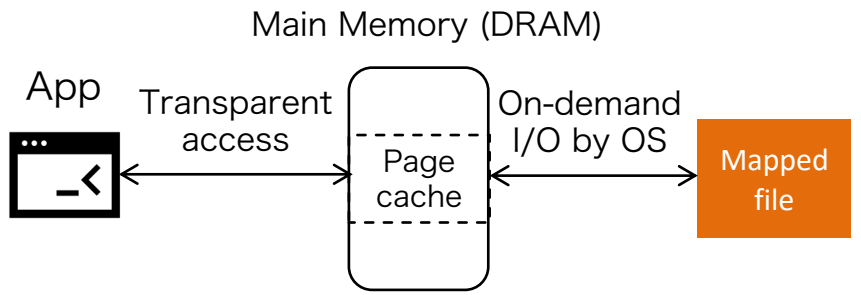
- Data serialization is expensive
  - Dismantling and assembling large complex data structures is expensive in terms of performance and programming cost
- Should leverage the file system
  - Tremendous amount of powerful technologies
  - We can support various persistent memory types

Can we allocate data into file directly and store the data as is while providing transparent access 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





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

- Example

```
int fd = open("/mnt/ssd/file", O_RDWR); // Open a file


int size = 1024;
// Maps a file into main memory (1024 bytes)
int* array = (int*)mmap(NULL, size,
                        PROT_READ | PROT_WRITE,
                        MAP_SHARED, fd, 0);

close(fd);


array[0] = 10;

msync(array, size, MS_SYNC); // Flush dirty pages into the file
munmap(array, size); // Close the mapping
```

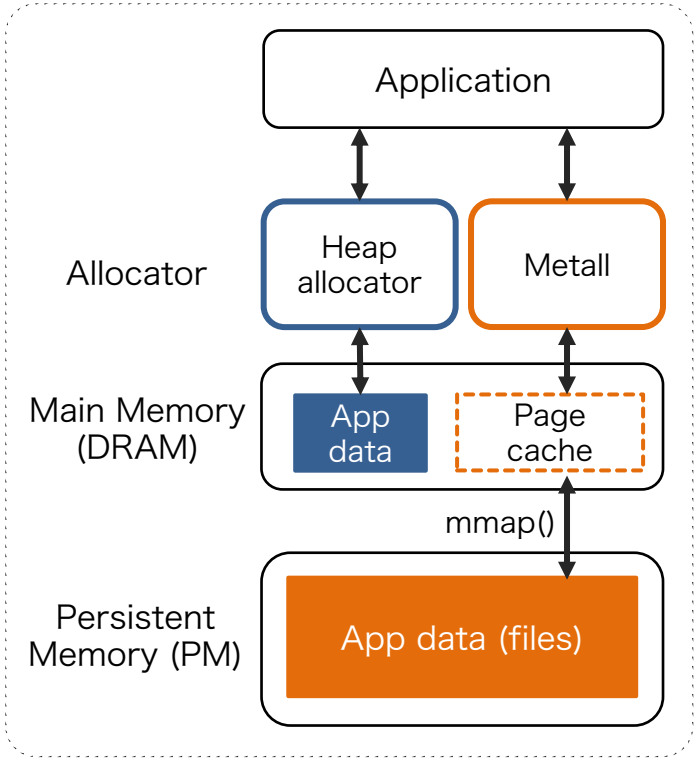
mmap is powerful; however,
calling mmap for every memory allocation is expensive

Metall
A C++ Allocator for Persistent Memory

[github.com/LLNL/metall]

Fork me on GitHub

- A memory allocator built on top of a memory mapping region
  - Designed to work on any devices with file system support (including *tmpfs*)
  - Can leverage file system technologies
- 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 synchronizes data with the PM (files)

Terminal

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

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

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

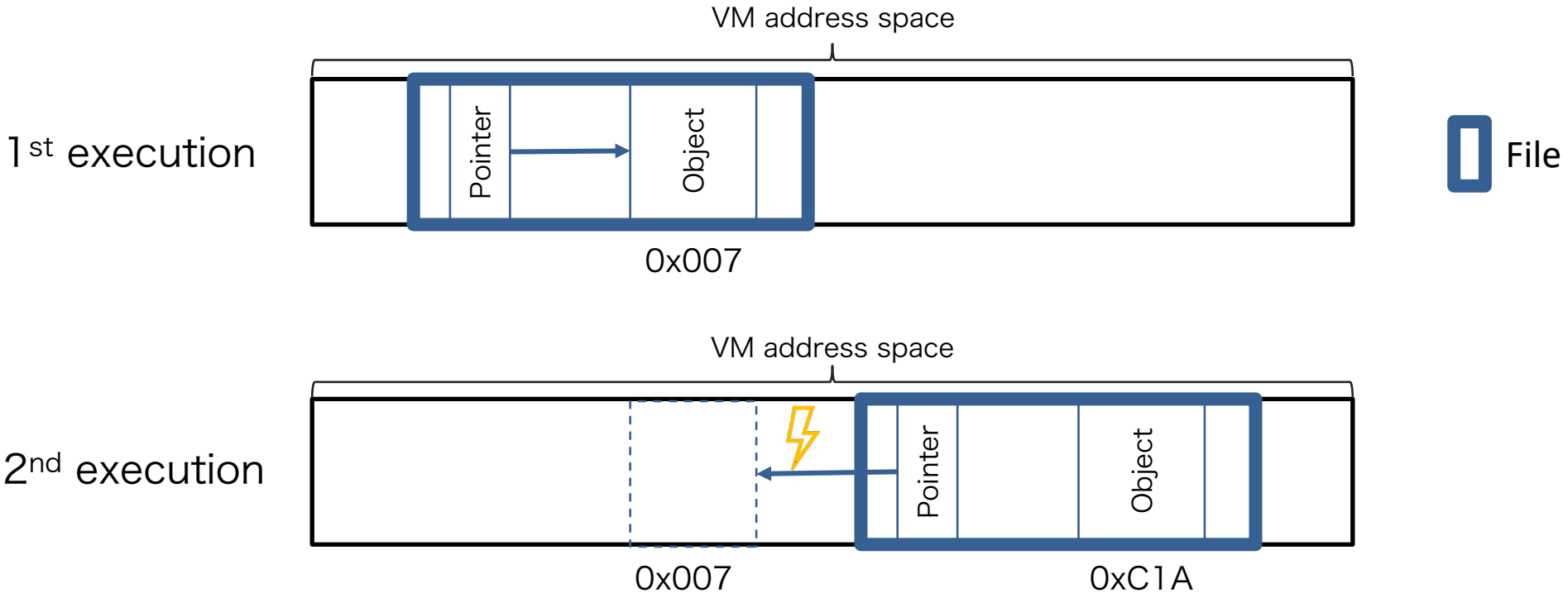
Reattach the data (open.cpp)

```
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)

Random Memory Placement



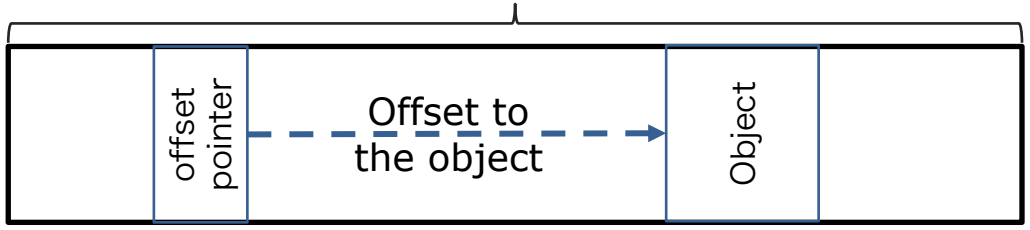
- Metall does not assume that file(s) are mapped to the same VM addresses every time

How to fix the random memory placement issue?

offset pointer

- An offset pointer holds the offset from itself to the object it points to

VM address space



Possible implementation

```
template <class T>
struct offset_pointer {
  int64_t offset;
  ... many methods ...
}
```

- Metall inherits offset_pointer implemented in Boost.Interprocess library (BIP)
- BIP's offset pointer works (almost) transparently with the raw pointer
- The concept of non-raw pointer is being integrated in C++

Usage examples

```
struct data { int n };
data d;
offset_ptr<data> p(&d);
p->n = 10;
p = nullptr;
```

```
int n[2];
offset_ptr<int> p(n);
p[0] = 1;
++p;
--p;
```

Solutions To Random Memory Placement

- Raw pointer
  - Must be replaced with offset pointers
- Reference, virtual function, and virtual base class
  - Must be removed since raw pointers are used
- STL Container
  - Some implementations do not support offset pointers fully
  - Boost.Container library is compatible with Metall
- Static data members are not supported

Persistence Policy — fine grained vs coarse grained

- Fine grained persistence policy
  - Synchronizes 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 this policy
  - Synchronizes data only when initiated by application
  - Could cause data inconsistency if there is a crash before synchronizing

Coarse grained persistence model in Metall

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

→ Data is consistent

Data could be inconsistent

→ Data is consistent

- Consistent mark
  - Metall leaves a mark (file) at the end of its destructor
  - The mark is deleted when Metall opens the data
- Read-only open mode
  - Writing to data allocated in Metall space causes a segmentation fault
    - Metall maps files with the read-only mode in mmap()
  - Metall does not delete the consistent mark

Snapshot/versioning in Metall

- Another way to create a consistent data

```
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/ssd2/data'
- '/mnt/ssd2/data' is consistent if snapshot() finishes correctly

Snapshot/versioning in Metall (cont'd)

- Demonstration of Metall's snapshot

create.cpp

```
metall::manager manager(metall::create_only, "/ssd/dir");

// Allocate an int object and assign 10
auto *n = manager.construct<int>("n")();
*n = 10;

manager.snapshot("/ssd/snapshot");

*n = 20;

// Assume that a fatal error happens here
```

open.cpp

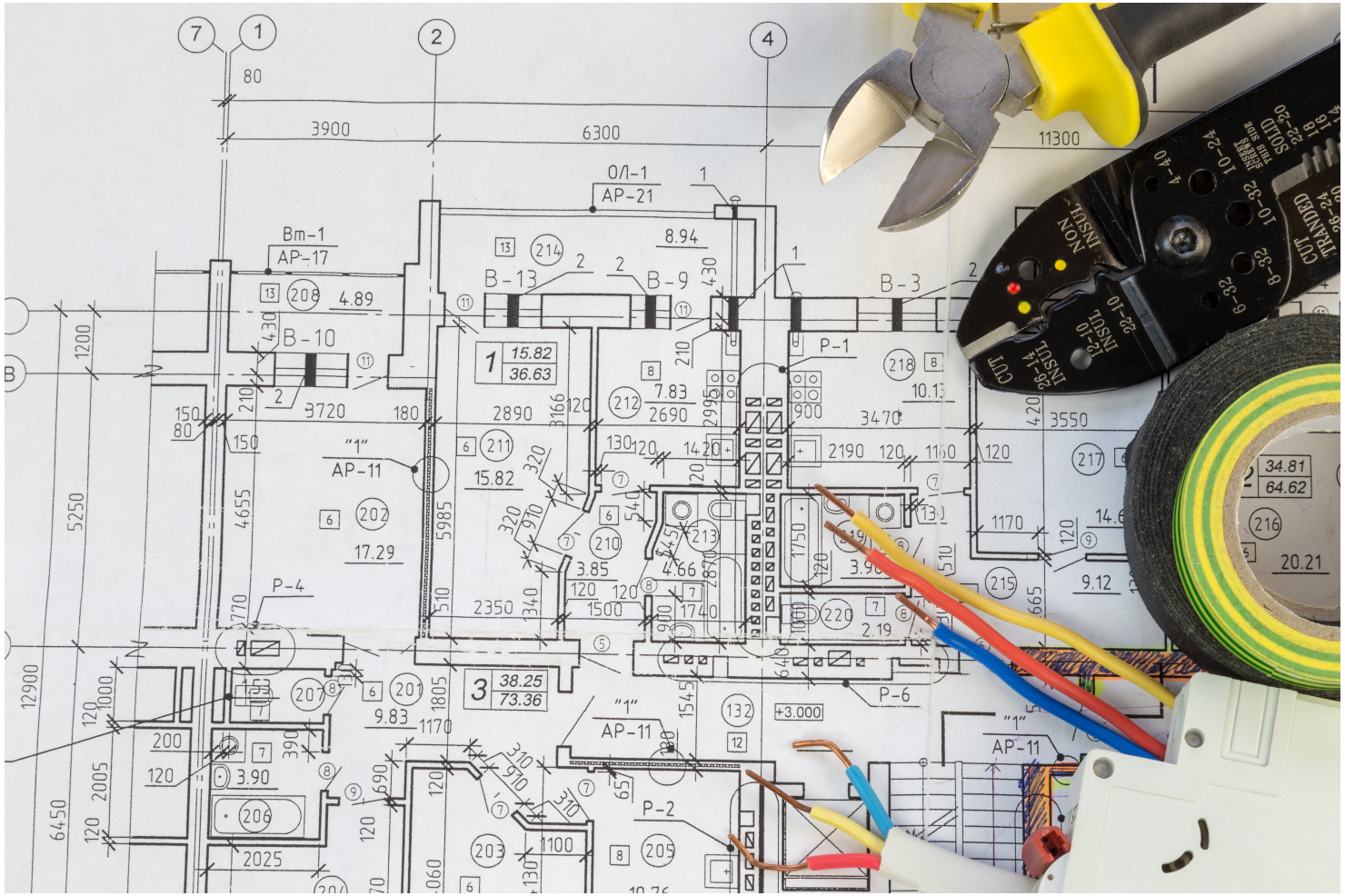
```
// 'flag' is false
bool flag = metall::manager::consistent("/ssd/dir");

if (metall::manager::consistent("/ssd/snapshot")) {

  // Open the snapshot
  metall::manager manager(metall::open_only, "/ssd/snapshot");

  int *n = manager.find<int>("n").first; // reattach 'n'
  std::cout << n; // 'n' is 10
}
```

Metall Internal Architecture



Key Design Points

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

Simplify implementation & increase speed

Internal Allocation Sizes

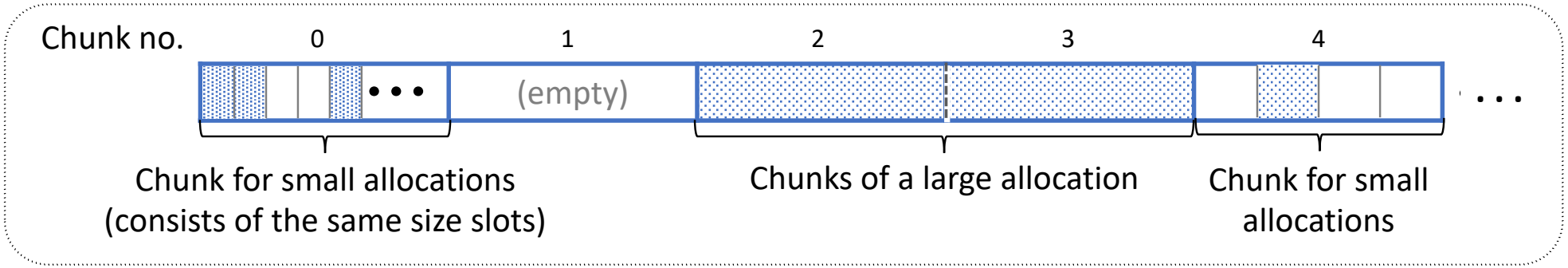
- Small size category (e.g., <= 1 MB)
  - Rounded up to the nearest internal allocation size
  - Internal sizes are designed to keep internal fragmentations < 25%[Supermalloc][jemalloc]

- Large size category (e.g., > 1 MB)
  - Rounded up to the nearest power of 2
  - Designed not to waste physical memory much
    - Thanks to demand paging, untouched pages do not consume physical memory
    - Worst case: 1.6% when allocating 1MB + 1 B with 4 KB page

Metall Internal Architecture

Application Heap Segment & Allocation Sizes

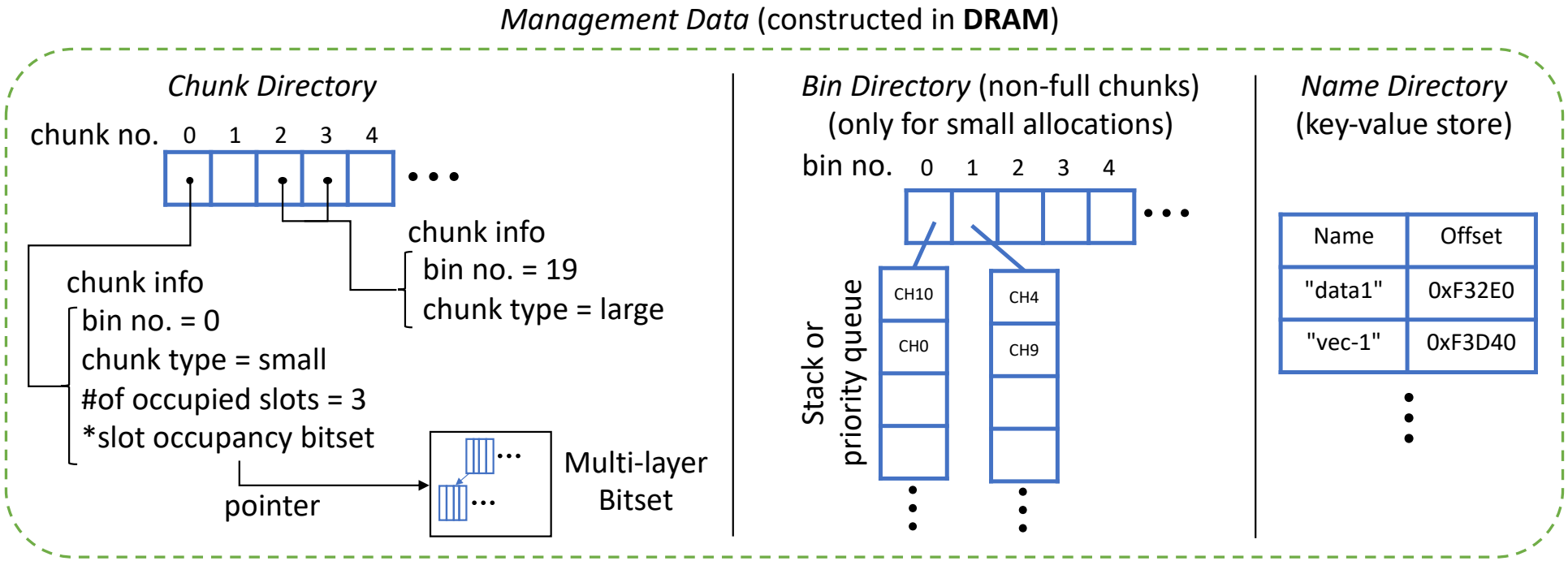
- Application heap segment
  - All application data (allocated by Metall) are stored in this region
  - Reserves a large (e.g., a few TB) continuous VM region in the process's address space
  - Maps backing files to the VM region on demand



The default chunk size is 2 MB

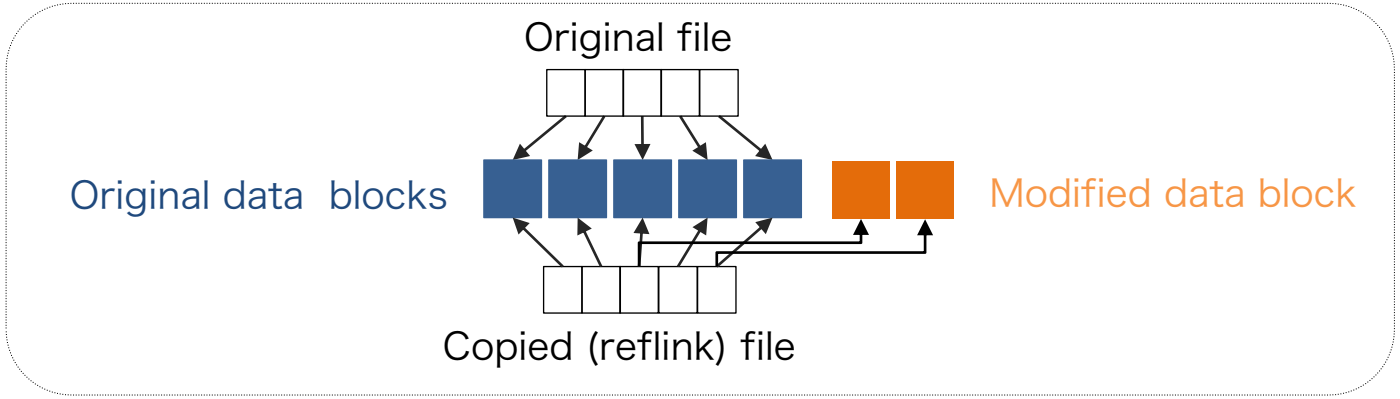
Memory Allocation Management Data (SLUB allocator)

- Allocated in DRAM, separating from application heap segment to improve data locality
  - Unserialized/serialized when Metall's constructor/destructor is called
  - Employs state-of-the-art allocation algorithms
  - Free-slot caches
    - CPU core level to improve multi-thread performance



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)

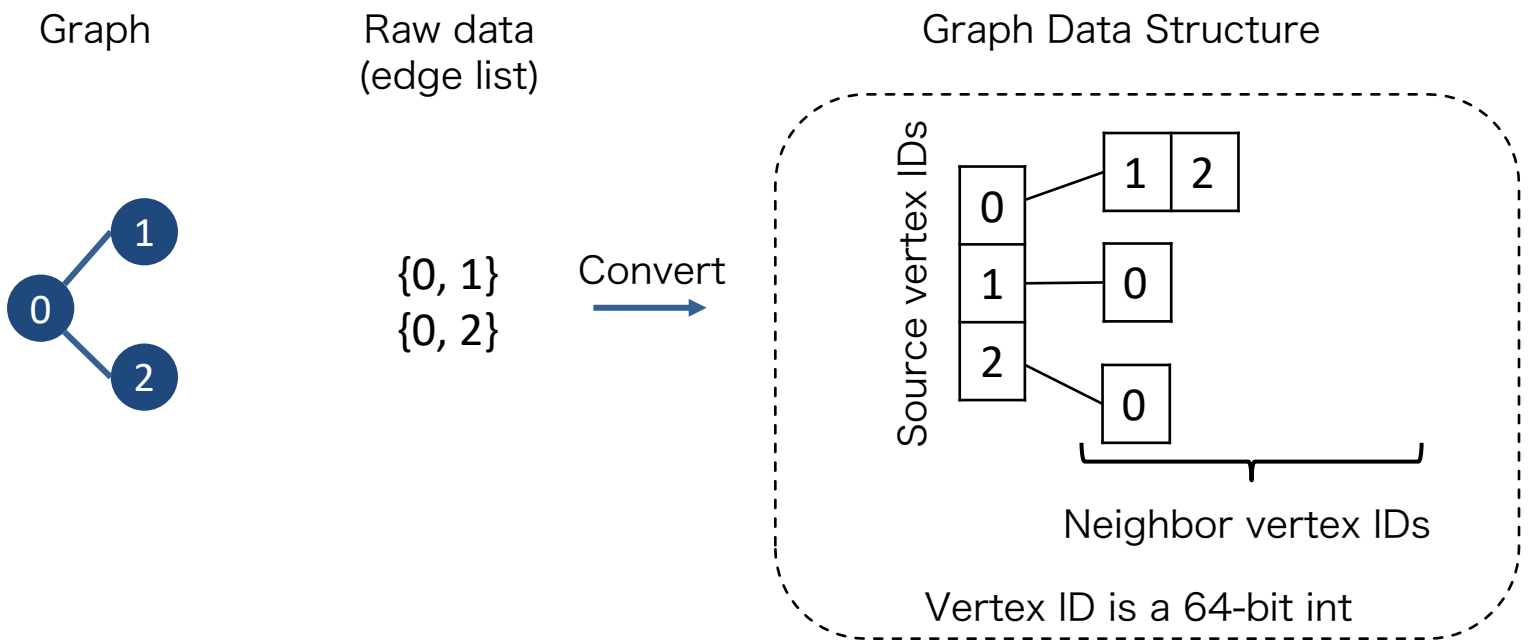


  - In case reflink is not supported by the filesystem, Metall automatically falls back to a regular copy

Evaluation

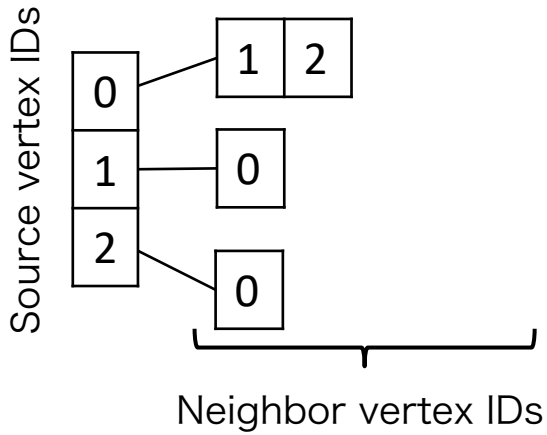
Evaluation
Graph Construction Benchmark

- A necessary step before performing actual graph analytics
- Partition and ingest raw graph data into a memory access efficient data structure
- Often more expensive graph analytics step



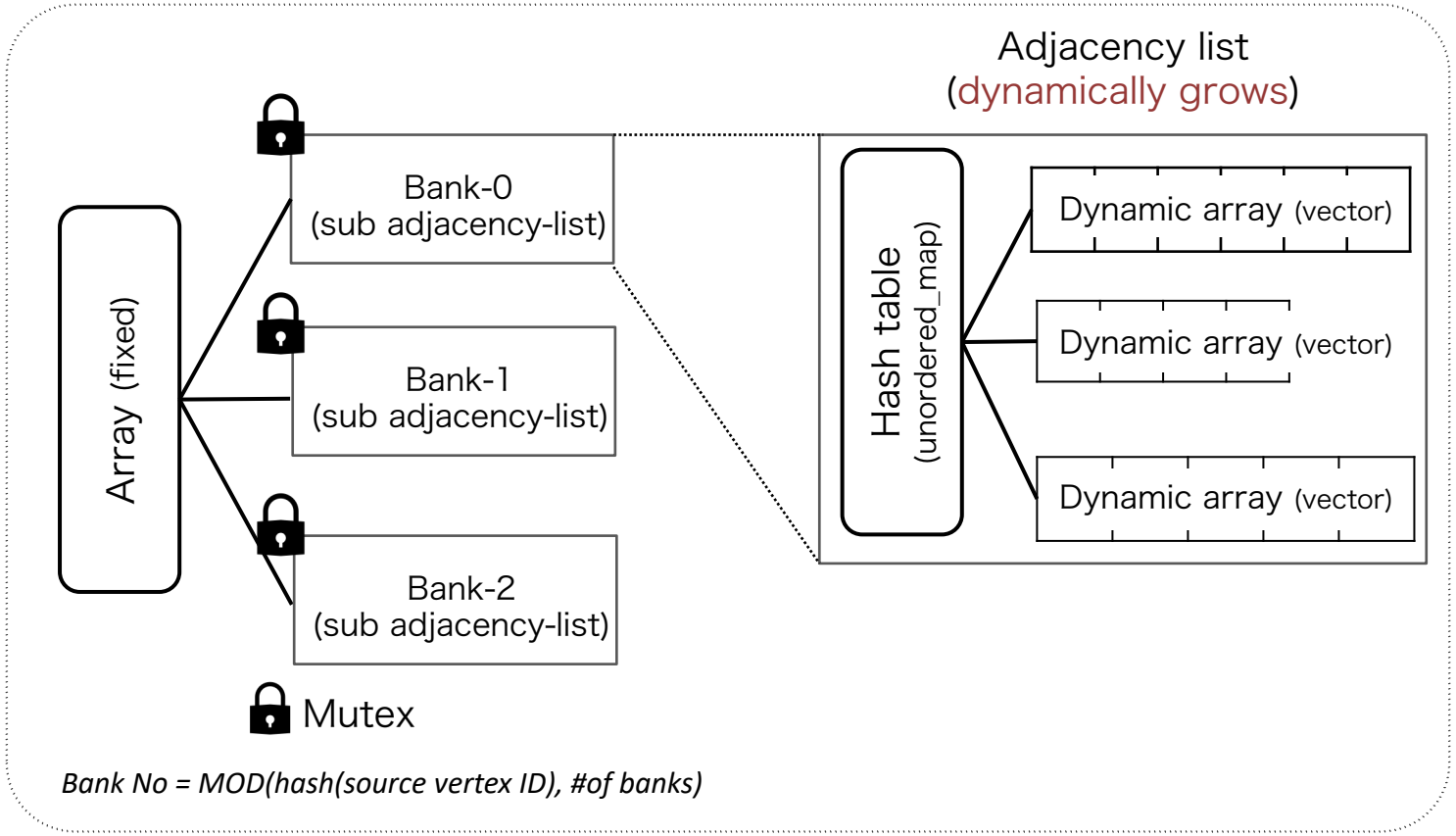
Evaluation
Graph Data Structure

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



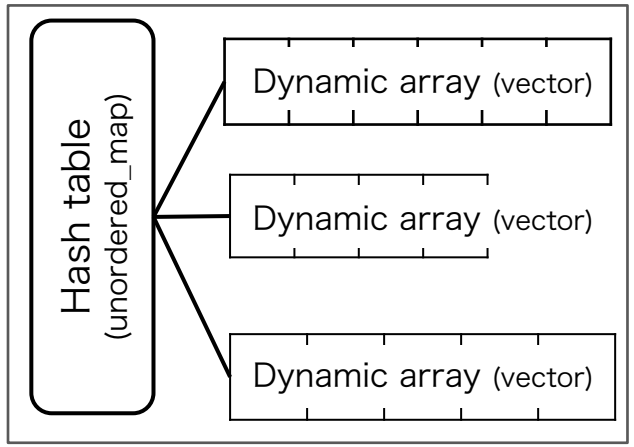
Vertex ID is a 64-bit int

Multi-banked concurrent adjacency list



Evaluation
Adjacency List Implementation

Adjacency list
(dynamically grows)



Adjacency-list with the default allocator (std::allocator)

```
class AdjacencyList {

  using edgeVec = vector<int>;
  using vertexTable = unordered_map<int, edgeVec>;
  vertexTable table;

  AdjacencyList() : table {}

  void addEdge(int source, int target) {
    table[source].push_back(target);
  }

}
```

*some unimportant details are omitted

Evaluation
Allocator-Aware Adjacency List

- Adjacency list with a **custom allocator**

```
template <class Alloc = std::allocator<std::byte>>
class AdjacencyList {

  using edgeVec = vector<int, Alloc::rebind<int>::other>;

  using tableAlloc = Alloc::rebind<pair<int, edgeVec>>::other;
  using vertexTable = unordered_map<int, edgeVec, /* ... */, tableAlloc>;
  vertexTable table;

  AdjacencyList(Alloc alloc = Alloc()) : table(alloc) {}

  // No changes to this method
  void addEdge(int source, int target) {}
}
```

Changed to an allocator-aware data structure, following the C++ standard style (no code depends on Metall)

Evaluation

Allocate Adjacency List Using Metall

With Metall

```
using AdjList = AdjacencyList<metall::manager::allocator_type<std::byte>>;

metall::manager metall_mgr(metall::create_only, "/ssd/graph");

auto* adj = metall_mgr.construct<AdjList>("graph")
                                          (metall_mgr.get_allocator());

adj->addEdge(1, 2);
```

With std::allocator (allocate in DRAM, no persistency)

```
auto* adj = new AdjacencyList();
adj->addEdge(1, 2);
```

The same data structure can be used with std::allocator

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)

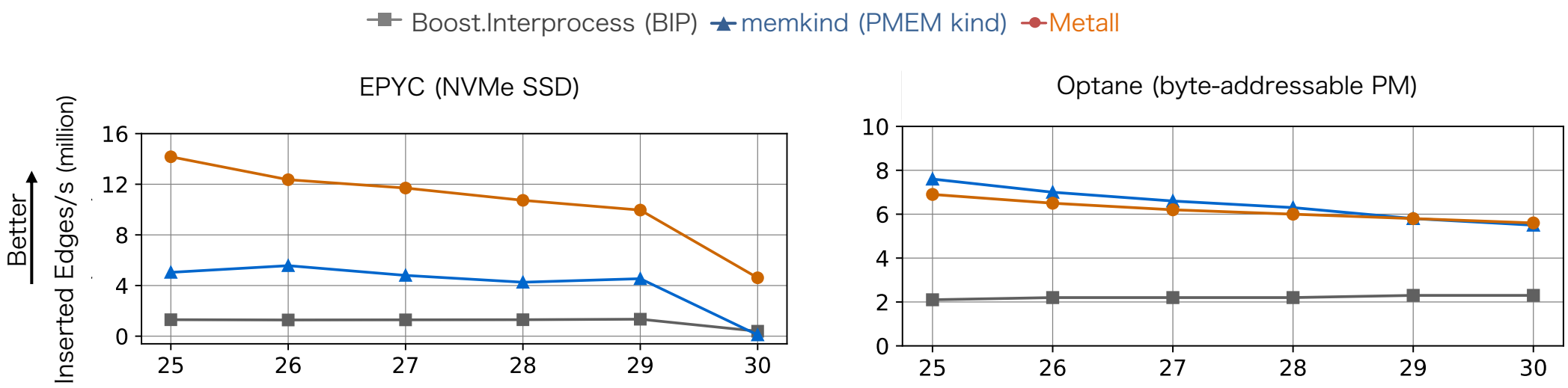
Storage	Intel Optane DC Persistent Memory (App Direct Mode + DAX)
DRAM	192 GB
CPU	Intel Skylake x 2 (96 threads)

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 volatile memory)



Graph SCALE (the number of inserted edges = 2^{SCALE} x 32)
(SCALE 30 is larger than DRAM)

Metall provides persistent memory features whereas PMEM kind does not

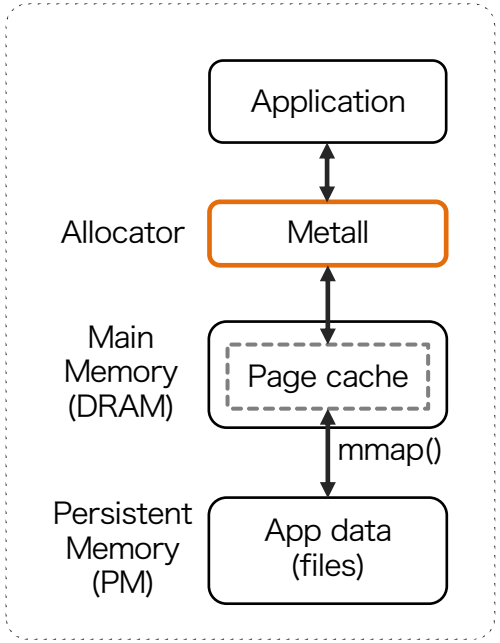
Related Work

- Heap allocators (e.g., jemalloc, tcmalloc, malloc implementations)
  - Many studies have been conducted and showed notable results
  - Cannot persistently store their internal structures
- Persistent Memory Allocator
  - 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)
  - Boost.Interprocess
    - Designed for interprocess communication (not designed as a persistent memory)
- Persistent Data Store
  - Hierarchical Data Format (HDF)
    - Allows applications to store data with portable formats
    - Metall is designed as a lightweight tool by limiting data portability

Metall is designed as a lightweight and high-performance persistent memory allocator with the coarse-grained persistence policy

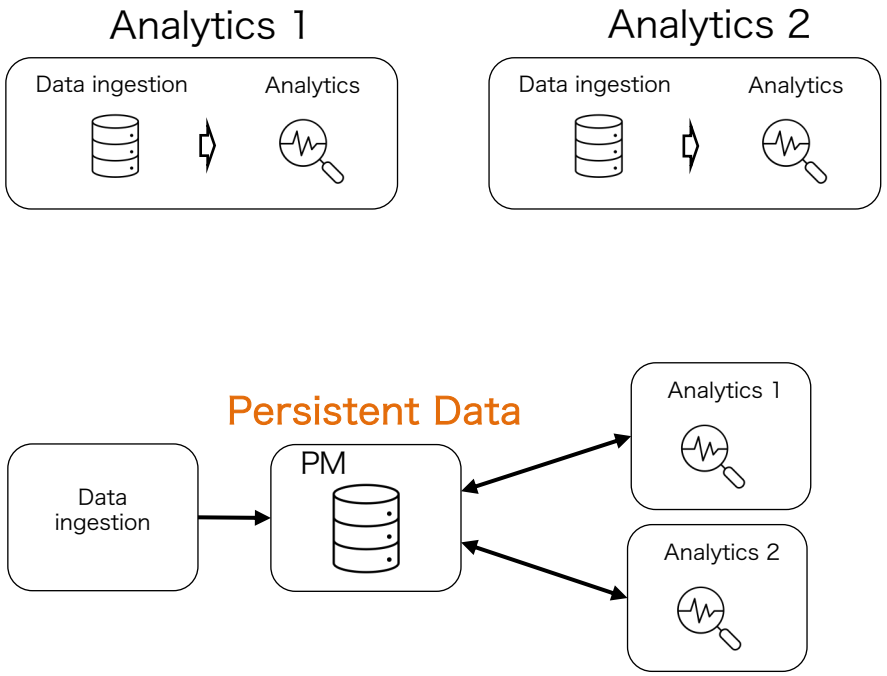
Summary (1/2)
Metall

- A memory allocator built on top of a memory mapping region
  - Designed to work on any devices with file system support (including *tmpfs*)
- Enables applications to allocate heap-based objects into PM, just like main-memory
- Rich API for custom C++ data structures
- Employs the coarse-grained consistency model
- Provides snapshot/versioning capabilities
- Incorporates state-of-the-art allocation algorithms

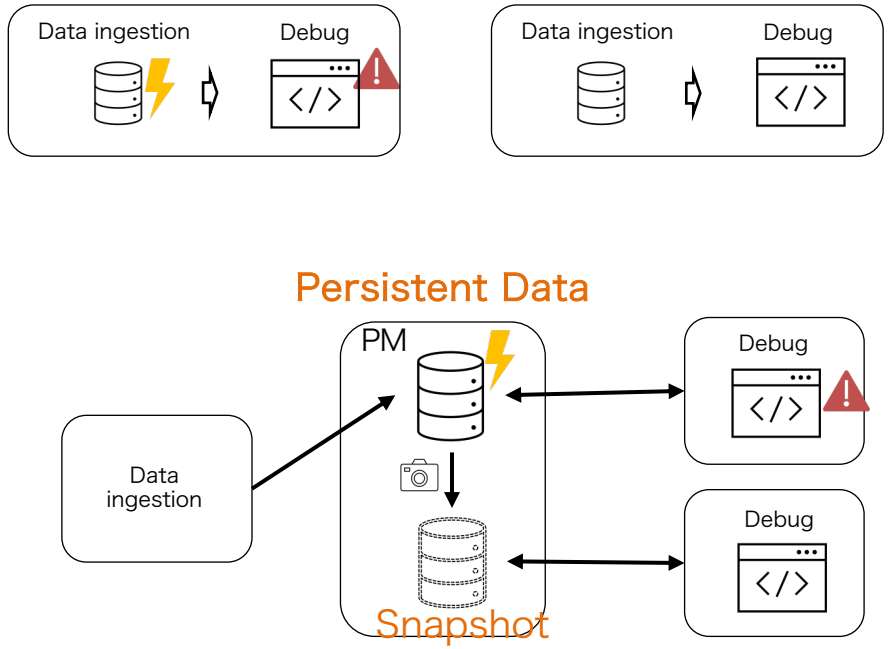


Summary (2/2)
Metall: A Persistent Memory Allocator For Data-Centric Analytics

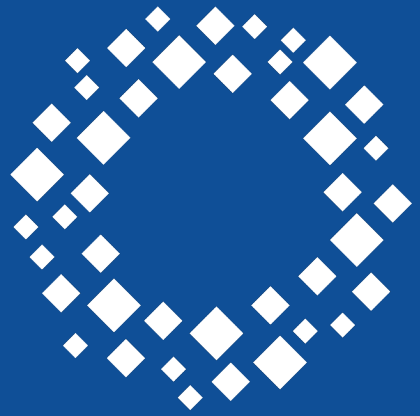
Data Analytics Workflow



Development/Debug Workflow



Metall enables applications to efficiently leverage persistent memory for data-centric computing



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