# Persistent memory hardware and programming

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# Persistent/Non-volatile memory

- Persistent/Non-volatile memory stores data after power off
  - SSDs (NAND Flash) are common examples
  - Similar technology in memory cards for your phones, cameras, etc…

- These store data persistently but are generally slow and less durable than volatile memory technologies (i.e. DRAM memory)

- Traditional non-volatile technology is accesses through a block device interface
  - Chunks of data at a time (i.e. 4kb), asynchronous access

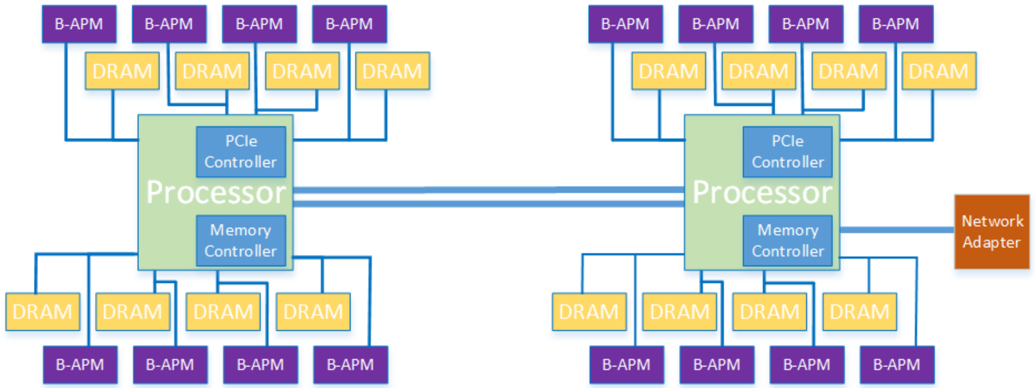
# NVDIMMs

- JEDEC standard on non-volatile memory DIMMs
- NVDIMM-F
  - Traditional flash solution with controller on board
  - NAND flash performance and size
- NVDIMM-N
  - DRAM with Flash for backup
  - Separate power supply (i.e. super capacitors) allow data to be copied to flash on power failure
  - Limited by DRAM size and capacitor sizes
  - DRAM performance and size
- NVDIMM-P
  - Channel support for mixed memory types
  - Protocol to enable transactional access
  - Different access latencies allowed between media types
  - Intel Optane DCPMM, technically, does not implement the NVDIMM-P standard, but it is conceptually NVDIMM-P
  - What I call Byte-Addressable Persistent Memory (B-APM)

# Intel Optane DCPMM

- Persistent/Non-volatile RAM/B-APM
  - Optane memory
- Much larger capacity than DRAM
  - Hosted in the DRAM slots, controlled by a standard memory controller
- Slower than DRAM by a small factor, but significantly faster than SSDs
- Read/write asymmetry and other interesting performance factors
- Cache coherent data accesses
  - Byte addressable (cache line)
- High endurance (5 year warranty)

# Placement




- As B-APM is in-node, placement is important
  - Configuration can be variable
  - Currently need one DRAM per memory channel
  - Can match DRAM-B-APM or have more B-APM
- Capacity (both DRAM and B-APM) affected
- Memory controller deals with mixed configuration
  - Variable latency on memory DIMMs
  - Requires asynchronous or non-blocking memory operations
- Optane DIMMs can be striped on non-striped
  - One memory area per DIMM, or one memory area per socket, striped across DIMMs

# Optane DCPMM – NUMA issues

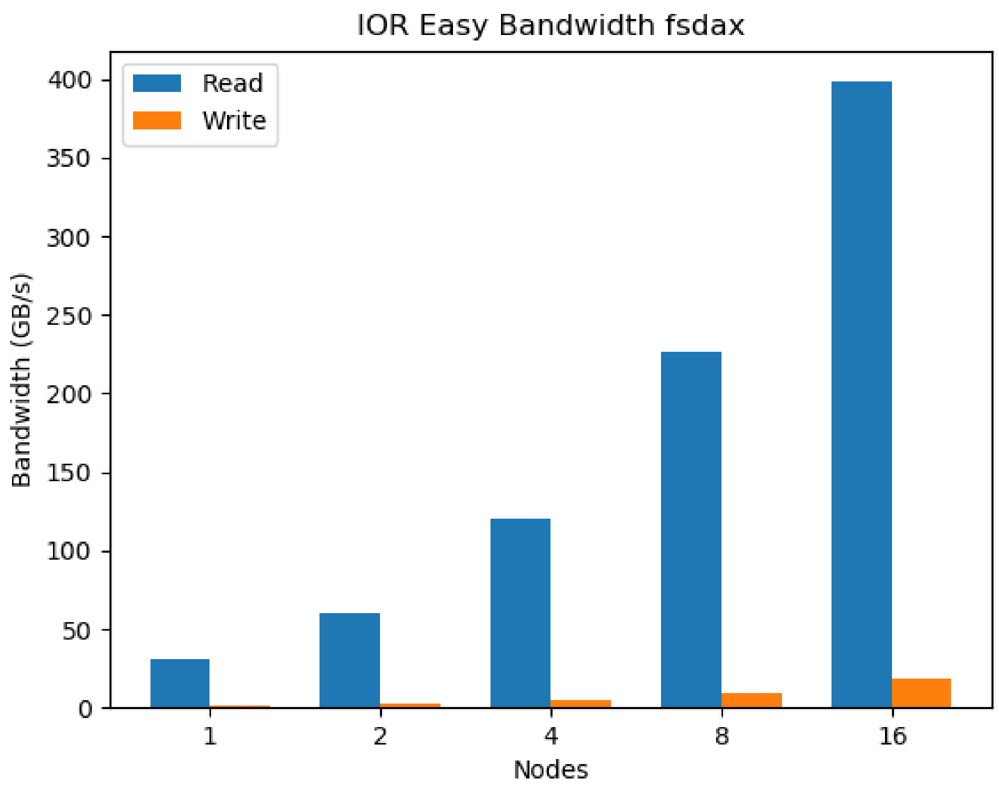
- Socket based systems means NUMA when not a single socket system
  - Performance dependent on using local memory
- Factor ~4x write performance for using local memory when fully populating nodes
- Factor ~2x read performance for using local memory when fully populating nodes
- Getting NUMA information in an application
  - Intel specific:

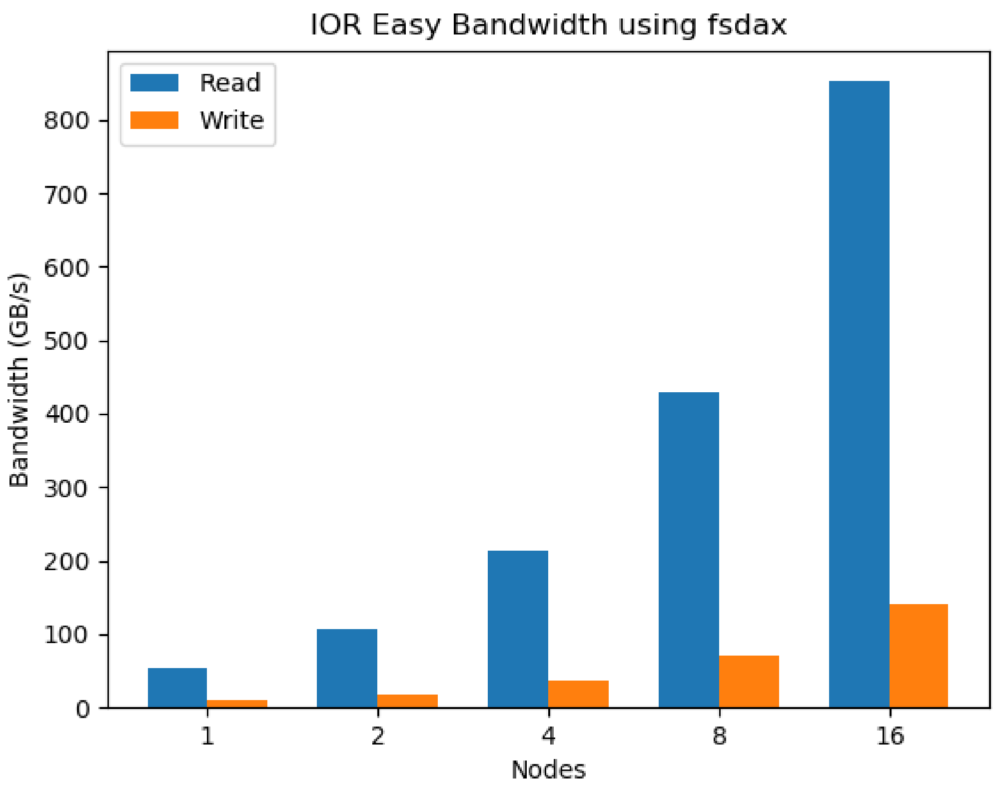
```
unsigned long GetProcessorAndCore(int *chip, int *core){
   unsigned long a,d,c;
   __asm__ volatile("rdtscp" : "=a" (a), "=d" (d), "=c" (c));
   *chip = (c & 0xFFF000)>>12;
   *core = c & 0xFFF;
   return ((unsigned long)a) | (((unsigned long)d) << 32);;
}
```

  - Processor agnostic

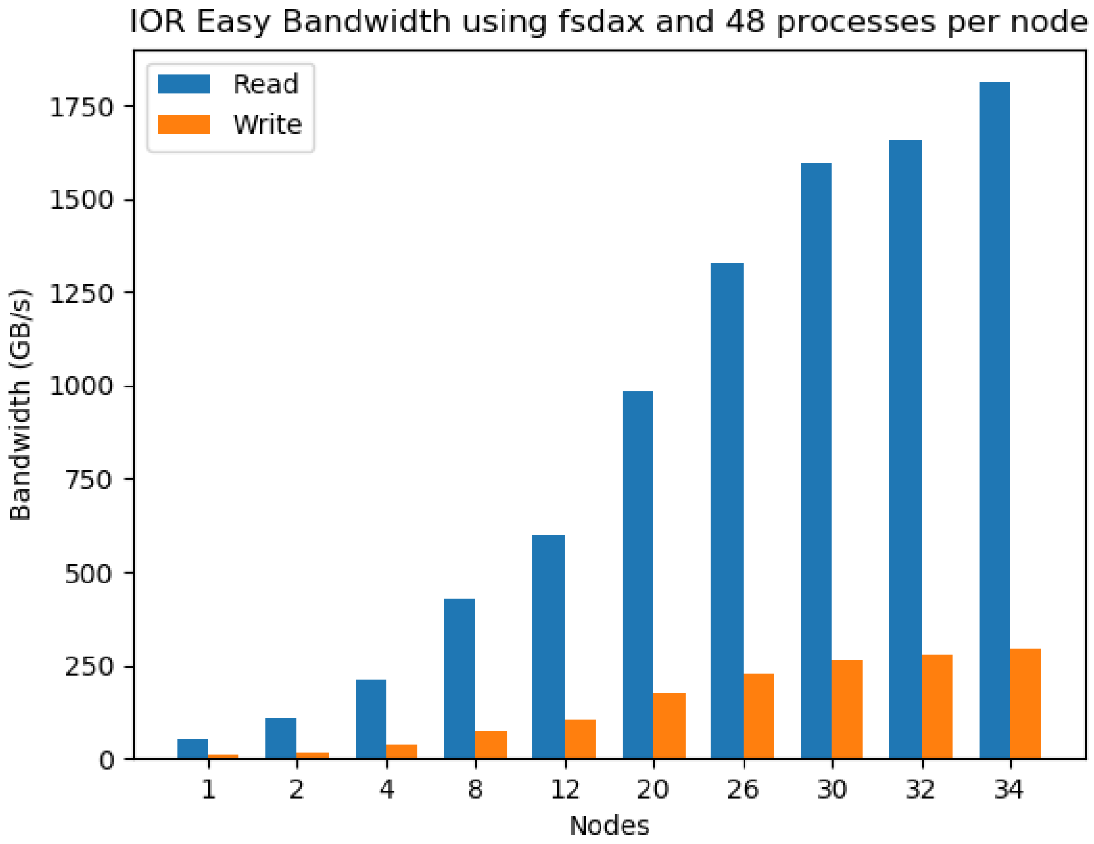
```
unsigned long GetProcessorAndCore(int *chip, int *core){
   return syscall(SYS_getcpu, core, chip, NULL);
}
```

# Optane NUMA performance



# Optane performance



# Optane Performance asymmetry

- Read is ~3x slower than DRAM
- Write is ~7x slower than DRAM
- Read is 4x-5x faster than write for Optane
- Write queue issues can mean variable performance
  - Optane has active write management
  - On-DIMM controller
- Accesses are coalesced into blocks of i.e. 256 bytes

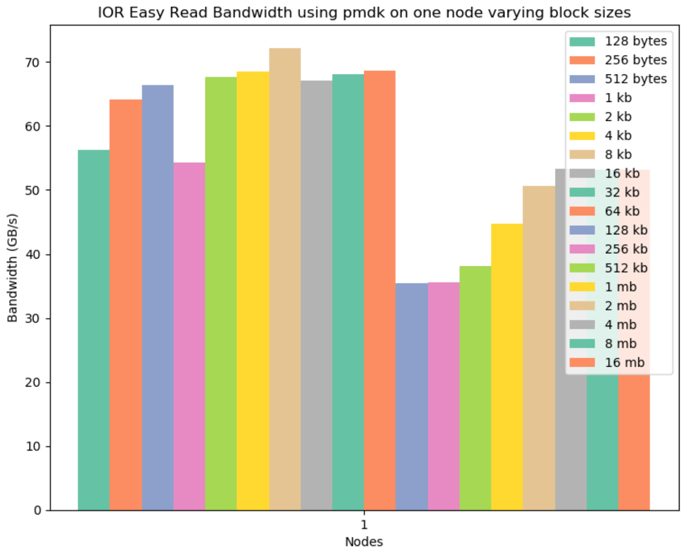
## INTEL® OPTANE™ DC PERSISTENT MEMORY PERFORMANCE DETAILS

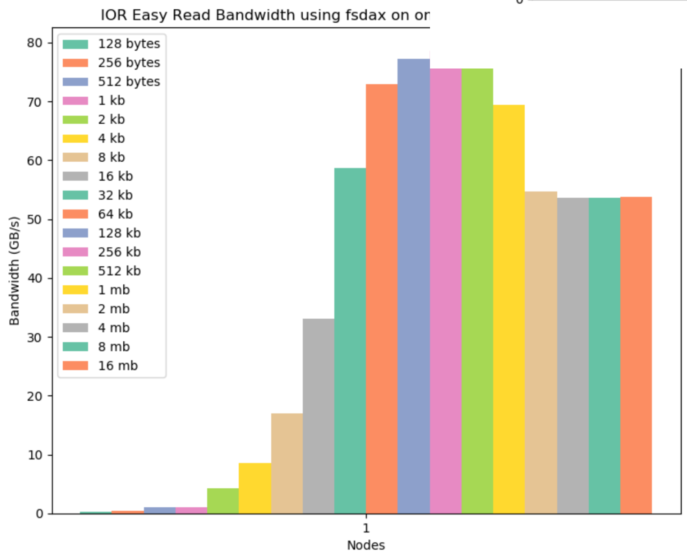
- Intel® Optane™ DC persistent memory is programmable for different power limits for power/performance optimization
  - 12W – 18W, in 0.25 watt granularity - for example: 12.25W, 14.75W, 18W
  - Higher power settings give best performance
- Performance varies based on traffic pattern
  - Contiguous 4 cacheline (256B) granularity vs. single random cacheline (64B) granularity
  - Read vs. writes
  - Examples:

| Granularity | Traffic | Module | Bandwidth |
|---|---|---|---|
| 256B (4x64B) | Read | 256GB, 18W | 8.3 GB/s |
| 256B (4x64B) | Write | | 3.0 GB/s |
| 256B (4x64B) | 2 Read/1 Write | | 5.4 GB/s |
| 64B | Read | | 2.13 GB/s |
| 64B | Write | | 0.73 GB/s |
| 64B | 2 Read/1 Write | | 1.35 GB/s |

# Byte Addressable/Granularity

- A key feature of B-APM
  - Data access is the same cost for any size of operation
    - Not really, but much closer than for standard files
- Byte-addressable just like standard memory
  - Individual bytes accessible without large operations
  - In reality, cache-line level access
- I/O and data operations can be small
  - Restructure I/O/applications

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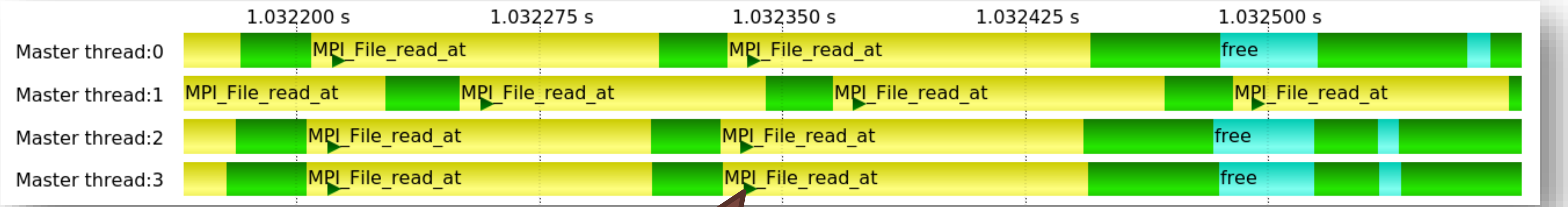
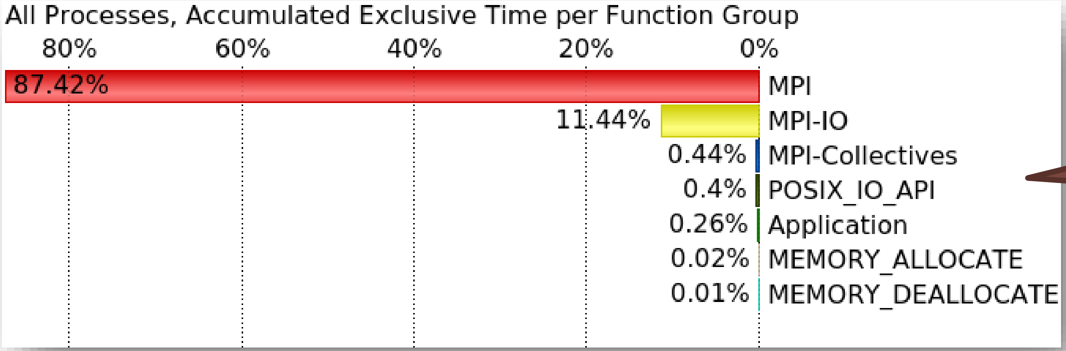
# Granularity




Individual I/O Operation




I/O Runtime Contribution

# Standard I/O Programming

```
my_file = open("data_out.dat", O_RDWR);
read(my_file, a, bufsize);
write(my_file, b, bufsize);
close(my_file);
```

```
open(fid, "checkpoint.dat")
do n = 0,2*nharms
    write(fid)(((q(i,j,k,n),i=-1,imax1),j=-1,jmax1),k= 1,kmax1)
end do
close(fid)
```

# Standard I/O Programming

- Writing to O/S buffer, operating system writes that back to the file
  - Potential for O/S caching
  - Writes data in large chunks, bad for random access
  - Requires interaction with O/S
  - I/O consistency application responsibility
    - Flush required to ensure actual persistency

- Required because of the nature of previous I/O devices
  - Asynchronous
  - I/O controller
  - Shared

# Parallel I/O Programming

- Library function to write to shared or separate files
- Library collects data and orchestrates writing to the actual file
- Still block based ultimately, requires parallel filesystem to enable multiple processes writing at once to the same file
  - Or multiple processes accessing multiple files at once

```
call mpi_file_write(fid, linelength, 1, MPI_INTEGER, MPI…
```

# Optimising I/O

- Optimising I/O performance can be done in a number of ways
  - Ensuring the minimal number of actual block writes is done
  - Ensure the minimal number of filesystem operations are performed
  - Use faster I/O hardware
  - Use multiple bits of I/O hardware
  - Map the file to memory for I/O operations
- Optimising hard for a range of use cases
  - Small I/O operations
  - Non-contiguous I/O operations
  - Contention on shared resources (network or filesystem)

# Memory-mapped files

```
my_file = open("data_file.dat", O_RDWR);
data = mmap(NULL, filesize, PROT_READ|PROT_WRITE, MAP_SHARED, my_file, 0);
close(fd);
data[0] = 5.3;
data[1] = 75.4;
```

- Memory-mapping a file copies the file into main memory
  - Requires sufficient main memory to contain the file
- Operations can then be undertaken on that data in standard memory format
  - Load/store, cache-line level accesses
- Persistence to file requires flush
  - msync
  - Done on page level
  - Every dirty page written back to file system
- Page cache supports dirty flag
  - Only dirty pages written back
- Volatile until persisted

# PMDK

- To utilise persistent memory functions are need to allocated, deallocate, and persist memory in the address ranges of the NVDIMMs

- mmap approach is adopted
  - Except the persistent memory data is not mapped into DRAM
  - And there is no initial read of data because it is already in persistent memory
  - And persisting is done on cache lines

- Functions to help run on systems with and without persistent memory

- PMDK has various different approaches for using persistent memory
  - https://github.com/pmem/pmdk

# pmem

- pmem lowest level approach available in PMDK
- Functions to memory map persistent memory and persist data to the hardware
- Functions to do optimised memcpy, memmove etc...
- User's responsibility to ensure data is safely persisted

# pmem example

```
double *a, *b, *c;
pmemaddr = pmem_map_file(path, array_length, PMEM_FILE_CREATE|PMEM_FILE_EXCL,
                         0666, &mapped_len, &is_pmem)
a = pmemaddr;
b = pmemaddr + (*array_size+OFFSET)*BytesPerWord;
c = pmemaddr + (*array_size+OFFSET)*BytesPerWord*2;

#pragma omp parallel for
for (j=0; j<*array_size; j++){
   a[j] = b[j]+scalar*c[j];
}
pmem_persist(a, *array_size*BytesPerWord);
pmem_unmap(pmemaddr, mapped_len);
remove(path);
```

# pmem_map_file

```
void *pmem_map_file(const char *path, size_t len, int flags, mode_t
mode, size_t *mapped_lenp, int *is_pmemp);
```

- Path is the location of the pmem mount
  - `/mnt/pmem_fsdax0`
  - `/dev/dax0.0`

- Flags
  - **PMEM_FILE_CREATE** - Create the file named *path* if it does not exist. *len* must be non-zero and specifies the size of the file to be created. If the file already exists, it will be extended or truncated to *len*.
  - **PMEM_FILE_EXCL** - If specified in conjunction with **PMEM_FILE_CREATE**, and *path* already exists, then **pmem_map_file**() will fail with **EEXIST** (fsdax only)
  - **PMEM_FILE_TMPFILE** - Create a mapping for an unnamed temporary file (fsdax only)

- For devdax *len* must be equal to either 0 or the exact size of the device

# pmem_persist

```
void pmem_persist(const void *addr, size_t len);
```

- Force the data at address addr to addr+len to be written to the persistent media.
- If this is on B-APM it will write directly back to the hardware (no O/S calls)
- It may write slightly more back (cache line size) than specified in len
- Before this call data *may* be persisted, but no guarantee

```
int pmem_msync(const void *addr, size_t len);
```

  - Works on non-B-APM as well

```
Void pmem_persist(const void *addr, size_t len){
/* flush the processor caches */
      pmem_flush(addr, len);
/* wait for any pmem stores to drain from HW buffers */
      pmem_drain();
}
```

# Memory operations

```
void *pmem_memmove_persist(void *pmemdest, const void *src, size_t len);
void *pmem_memcpy_persist(void *pmemdest, const void *src, size_t len);
void *pmem_memset_persist(void *pmemdest, int c, size_t len);
```

- Copy, move, and set functions that automatically persist the data as well
- For control of persistence using the standard functions instead

```
void * pmem_memmove_persist(void *pmemdest, const void *src, size_t len){
      void *retval = memmove(pmemdest, src, len);
      pmem_persist(pmemdest, len);
      return retval;
}
```

# pmem2

- Recognised power failure domains at the software level
  - Processor
  - Memory Controller
  - Nothing
- Enables configuration of persistent granularity for data structures
  - `PMEM2_GRANULARITY_BYTE`
  - `PMEM2_GRANULARITY_CACHE_LINE`
  - `PMEM2_GRANULARITY_PAGE`
- Provides optimised memory operations to work with these different configurations
  - `pmem2_get_persist_fn`
  - `pmem2_get_flush_fn`, `pmem2_get_drain_fn`
  - `pmem2_get_memcpy_fn`, `pmem2_get_memmove_fn`

```
int fd;
struct pmem2_config *cfg;
struct pmem2_map *map;
struct pmem2_source *src;
pmem2_persist_fn persist;

fd = open(argv[1], O_RDWR);
pmem2_source_from_fd(&src, fd);
pmem2_config_set_required_store_granularity
(cfg, PMEM2_CACHE_LINE);
pmem2_map_new(&map, cfg, src);

char *addr = pmem2_map_get_address(map);
size_t size = pmem2_map_get_size(map);

strcpy(addr, "hello, persistent memory");

persist = pmem2_get_persist_fn(map);
persist(addr, size);

pmem2_unmap(&map);
pmem2_source_delete(&src);
pmem2_config_delete(&cfg);
```

# libpmem(2)

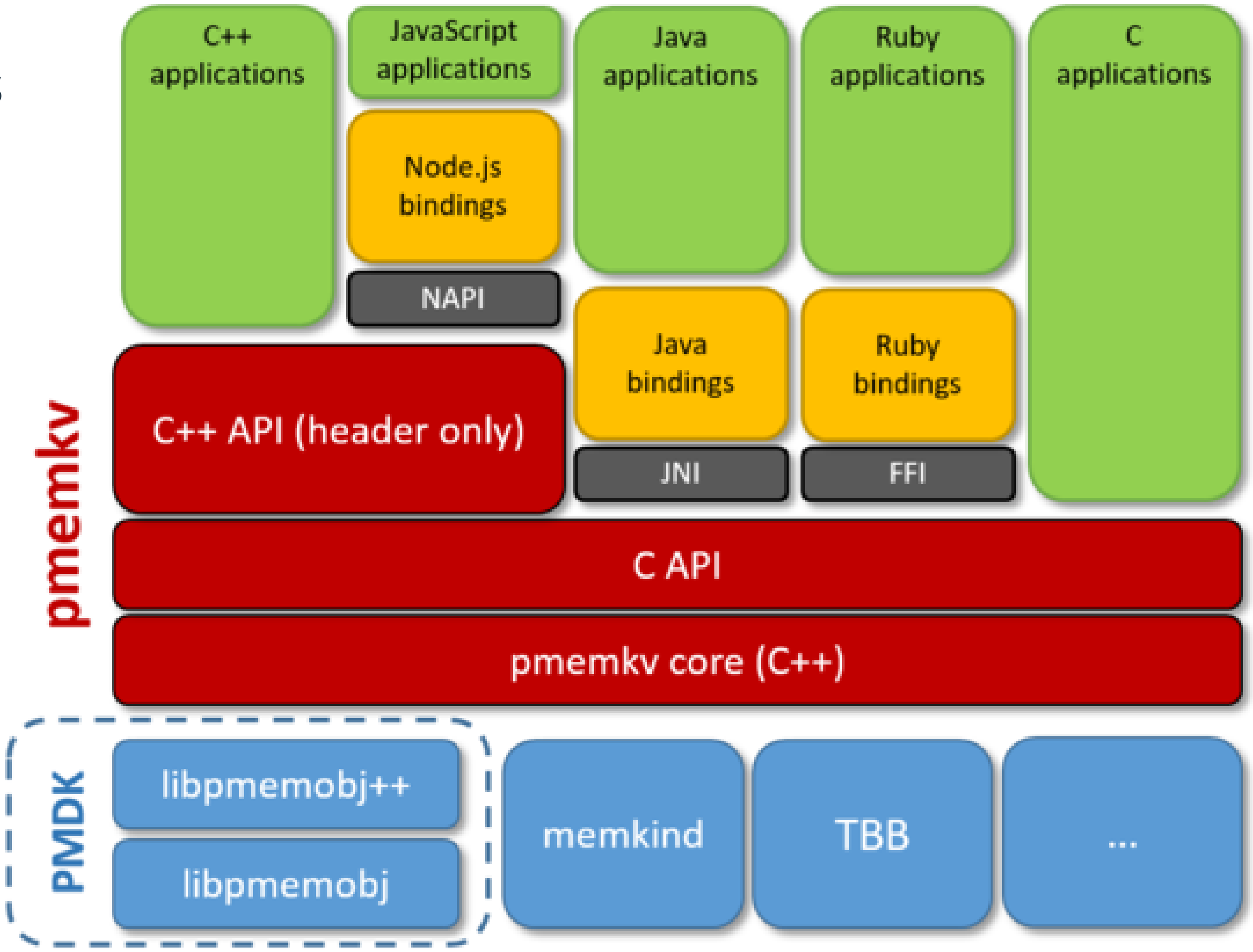
- Basic persistence functionality provided by the PMDK pmem library
  - Required if you want to use the persistent feature of persistent memory
- If large memory is all that is required libmemkind is available
- pmem defers responsibility to the programmer to ensure persistence is properly handled
  - Separates out memory creation and persistent calls
  - Enables control over persistent granularity
  - Enables maximum performance
  - But also maximum danger

# PMDK higher level options

- libpmemobj
  - Transactional object store
  - Providing memory allocation, transaction
- Pools
  - libpmemblk
    - Blocks, all the same size, that are atomically updated
  - libpmemlog
    - Log file on persistent memory
- pmemkv
  - Key value store

# pmemkv

- Storage engine with simple operations
  - Start
  - Stop
  - Put
  - Get
  - Remove
  - Exists
- Also further iterator operations
  - Count
  - All
  - Each



# pmemkv

```
int main(){
  KVEngine* kv = KVEngine::Start("vsmap","{\"path\":\"/dev/shm/\"}");
  KVStatus s = kv->Put("key1", "value1");
  string value;
  s = kv->Get("key1", &value);
  s = kv->Remove("key1");
  delete kv;
  return 0;
}
```

# pmemkv

## Storage Engines

`pmemkv` provides multiple storage engines that conform to the same common API, so every engine can be used with all language bindings and utilities. Engines are loaded by name at runtime.

| Engine Name | Description | Experimental? | Concurrent? | Sorted? |
|---|---|---|---|---|
| blackhole | Accepts everything, returns nothing | No | Yes | No |
| cmap | Concurrent hash map | No | Yes | No |
| vsmap | Volatile sorted hash map | No | No | Yes |
| vcmap | Volatile concurrent hash map | No | Yes | No |
| tree3 | Persistent B+ tree | Yes | No | No |
| stree | Sorted persistent B+ tree | Yes | No | Yes |
| caching | Caching for remote Memcached or Redis server | Yes | No | - |

Contributing a new engine is easy and encouraged!

# libpmemobj

- Object store with transactions
- Provides functions to create and manage data in persistent memory
- Provides macros and functions to add and remove data from object store
- Node local

```
PMEMobjpool *pmemobj_open(const char *path, const char *layout);
void pmemobj_close(PMEMobjpool *pop);
PMEMoid pmemobj_root(PMEMobjpool *pop, size_t size);
int pmemobj_tx_add_range(PMEMoid oid, uint64_t off, size_t size);
int pmemobj_tx_add_range_direct(const void *ptr, size_t size);
PMEMoid pmemobj_tx_alloc(size_t size, uint64_t type_num);
int pmemobj_tx_free(PMEMoid oid);
void *pmemobj_direct(PMEMoid oid);
TX_BEGIN(PMEMobjpool *pop) / TX_END
OID_NULL, OID_IS_NULL(PMEMoid oid)
```

# libpmemobj

```
/* TX_STAGE_NONE */

TX_BEGIN(pop) {
      /* TX_STAGE_WORK */
} TX_ONCOMMIT {
      /* TX_STAGE_ONCOMMIT */
} TX_ONABORT {
      /* TX_STAGE_ONABORT */
} TX_FINALLY {
      /* TX_STAGE_FINALLY */
} TX_END

/* TX_STAGE_NONE *
```

# libpmemobj c++

```
struct queue {
        void
        push(pmem::obj::pool_base &pop, int value){
                pmem::obj::transaction::run(pop, [&] {
                        auto node = pmem::obj::make_persistent<queue_node>();
                        node->value = value;
                        node->next = nullptr;

                        if (head == nullptr) {
                                head = tail = node;
                        } else {
                                tail->next = node;
                                tail = node;
                        }
                });
        }
}
```

# libpmemblk

- Designed for array of blocks
  - updates to a single block are atomic

```
int main(int argc, char *argv[]){
   const char path[] = "/mnt/pmem_fsdax0/myfile";
   PMEMblkpool *pbp;
   size_t nelements;
   char buf[ELEMENT_SIZE];
   pbp = pmemblk_create(path, ELEMENT_SIZE, POOL_SIZE, 0666);
   if (pbp == NULL)
      pbp = pmemblk_open(path, ELEMENT_SIZE);
   }
   /* how many elements fit into the file? */
   nelements = pmemblk_nblock(pbp);
   strcpy(buf, “starting time");
   pmemblk_write(pbp, buf, 5)
   pmemblk_read(pbp, buf, 10);
   pmemblk_set_zero(pbp, 5);
   pmemblk_close(pbp);
}
```

# libpmemlog

- B-APM resident log file
- Designed for append-mostly file
- Variable length entries

```
plp = pmemlog_create(path, POOL_SIZE, 0666);
plp = pmemlog_open(path);
data = "first thing";
pmemlog_append(plp, data, strlen(data)) ;
data = "second thing";
pmemlog_append(plp, data, strlen(data));
pmemlog_walk(plp, 0, printit, NULL);
```

# pmempool

- The lib, blk, and obj functions use memory pools that can be created and managed using the mempool functions

- You can create a memory pool:

```
pmempool create obj --layout=simplekv -s 100M /mnt/pmem-fsdax0/simplekv-simple
```

- You can also interact with memory pools, i.e.:

```
pmempool info /mnt/pmem-fsdax0/simplekv-simple
```

# Higher level functionality

- For object store and transactional support these libraries are the best choice
- Provide extra functionality that gives persistency support
  - Has associated performance overhead
- Similar to filesystem support for standard I/O
- If pure memory access is not the model, these are the functions to use
  - For pure memory access and manipulation the low level pmem will give best control and performance
- Files are a good starting point
  - But lack the granularity control and associated performance pmem gives

# Persistent Memory Summary

- Optane hardware is complicated
- Performance is workload dependent (when isn't it?)
- Targeted usage will be required for the best performance
- I/O performance has been problematic for a while anyway
- In-node storage complicates data access and sharing

# Object Stores

- Filesystems use Files as the container for blocks  of data and the lowest level of metadata granularity

- Object stores use Objects as the container for data elements and the lowest level of metadata granularity
  - Allows individual pieces of data to be stored, indexed, and accessed separately
  - Allows independent read/write access to “blocks” of data

# Object Stores

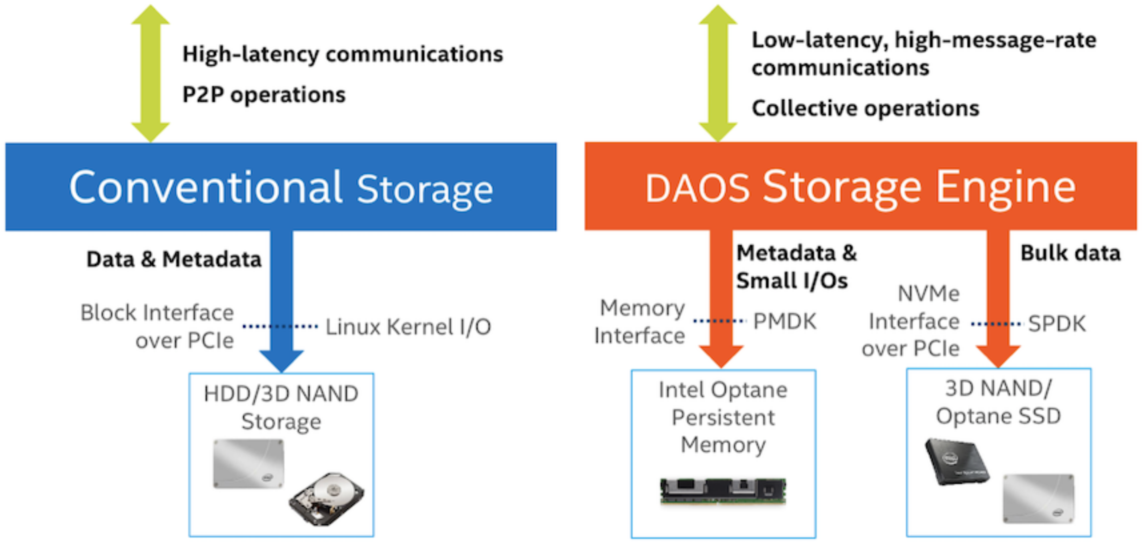
- Generally restricted interface
  - Put: Create a new object
  - Get: Retrieve the object
  - Removes the requirements for lots of functionality r.e. POSIX style I/O
- Traditionally objects are immutable
  - Once created cannot be changed
  - This removes the locking requirement seen for file writes
  - Makes updates similar to log-append filesystems, i.e. copy and update
- Object id generated when created
  - Used for access
  - Can be used for location purposes in some systems

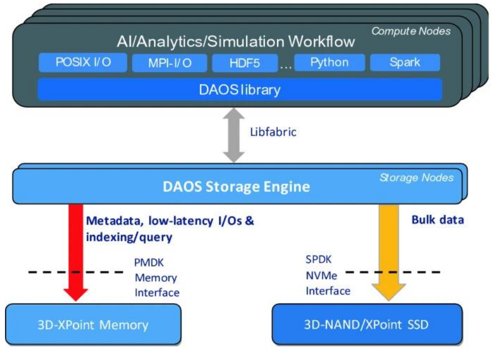
# Object Stores

- Generally have helper services and interfaces
  - Manage metadata
  - Permissions
  - Querying
  - Etc...
- Distribution and redundancy etc... part of the complexity
  - Often eventual consistency
- Lots of complexity in implementations
- Often web interfaces as part of the Put/Get interface

# DAOS

- Native object store on non-volatile memory and NVMe devices
- Pools
  - Define hardware range of data
- Containers
  - User space and data configuration definitions
- Objects
  - **Multi-level key-array** API is the native object interface with locality
  - **Key-value** API provides a simple key and variable-length value interface. It supports the traditional put, get, remove and list operations.
  - **Array API** implements a one-dimensional array of fixed-size elements addressed by a 64-bit offset. A DAOS array supports arbitrary extent read, write and punch operations.

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# Object store

- Software approach to granular data access
- Enabling generating and querying data on different "dimensions"
- Enabling data sizes to very whilst maintaining performance
- Enable "legacy" interfaces

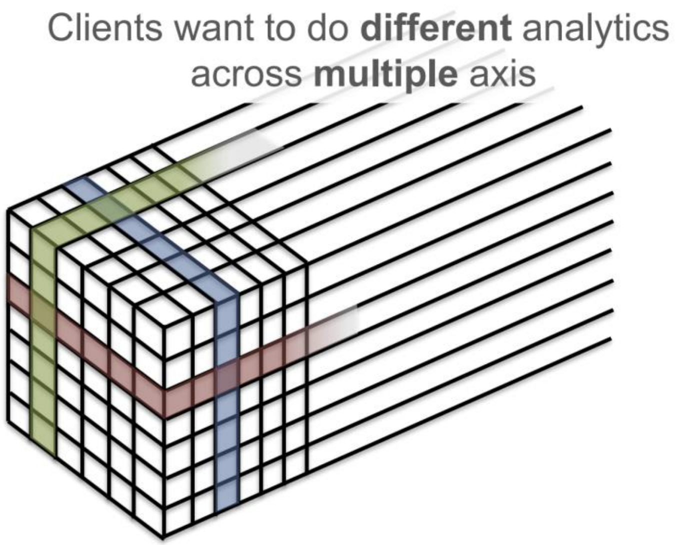


Image courteous of Tiago Quintino from ECMWF

# Practical Setup

- https://github.com/NGIOproject/PMTutorial
- Take IOR and STREAMS source code
- Run on the prototype
- Prototype is available at:

```
ssh ngio-adrianj.epcc.ed.ac.uk
```

- Then

```
ssh hydra-vpn.epcc.ed.ac.uk
```

- Then

```
ssh nextgenio-login2
```

- Using your guest account
- Practical source code is available at:

```
/home/nx01/shared/pmtutorial/exercises
```

- Using Slurm as the batch system
  ```
  sbatch --reservation=nx01_59 scriptname.sh
  ```
  Or
  ```
  srun --reservation=nx01_59 -N 1 --nvram-options=1LM:1000 --pty /bin/bash
  ```

**Emerg1ng_1nterfaces**

```
module load compiler
module load mpi
src/C/Makefile.config
mpicc -> mpiicc
```

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