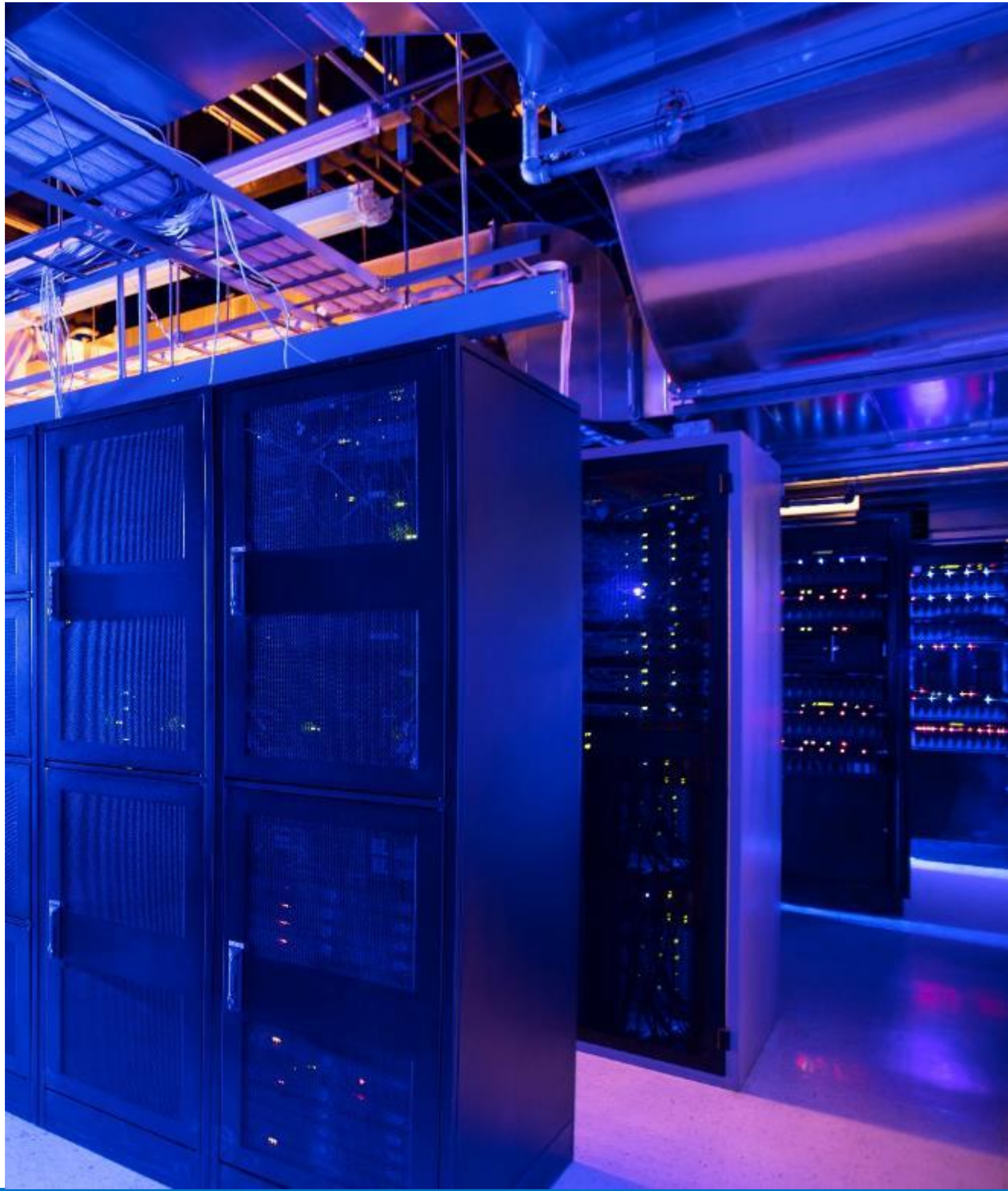
CREATING C++ APPS WITH LIBPMEMOBJ

Szymon Romik
<szymon.romik@intel.com>
Intel® Data Center Group

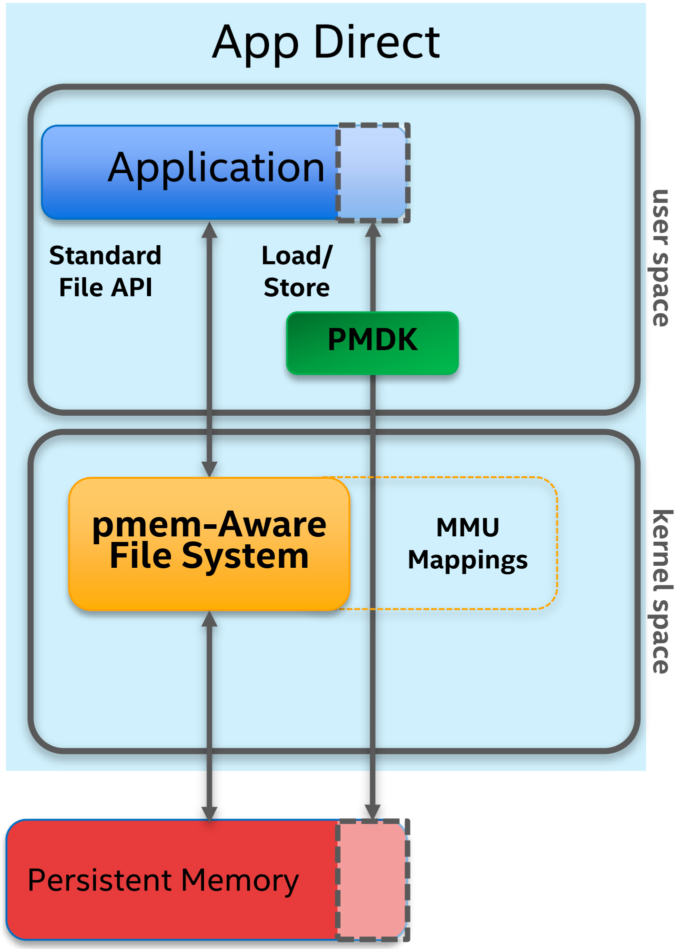
AGENDA

- App Direct mode
- PMDK and libpmemobj
- Persistent Memory pool
- Persistent pointer
- Root object
- Transactions
- `pmem::obj::p`
- Persistent Memory allocations
- Persistent Memory containers
- Example
- C++ standard limitations



APP DIRECT MODE

App Direct mode



Different modes for using Persistent Memory:

- Memory Mode
- Storage over App Direct
- App Direct

In-place persistence (no paging, context switching, interrupts, nor kernel code executes)

Byte addressable like memory (Load/store access, no page caching)

Cache Coherent

A pmem-aware file system exposes persistent memory to applications as files.

```
fd = open("/my/file", O_RDWR);
…
base = mmap(NULL, filesize,
                        PROT_READ|PROT_WRITE,
                        MAP_SHARED_VALIDATE|MAP_SYNC, fd, 0);
close(fd);
…
base[100] = 'X';
strcpy(base, "hello there");
msync(…);
…
```

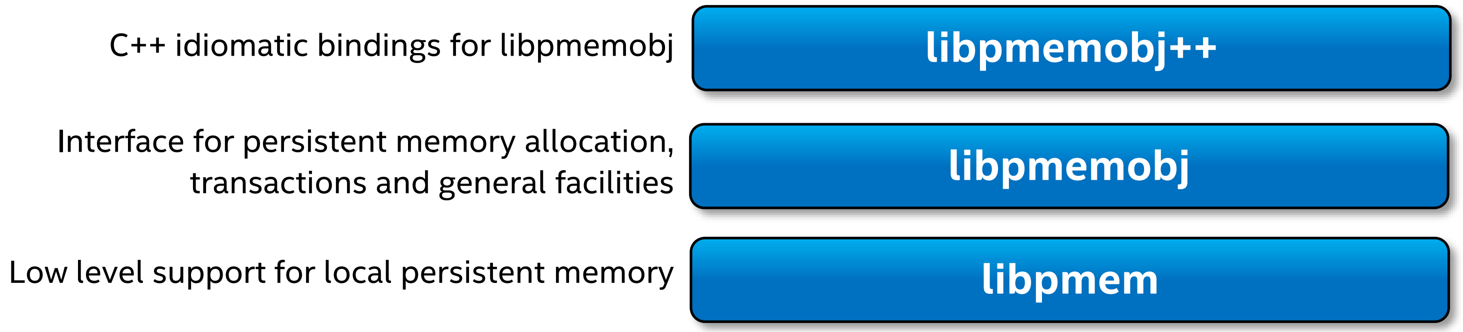
Application must take responsibility for recovery, consistency and atomicity.

PMDK AND LIBPMEMOBJ

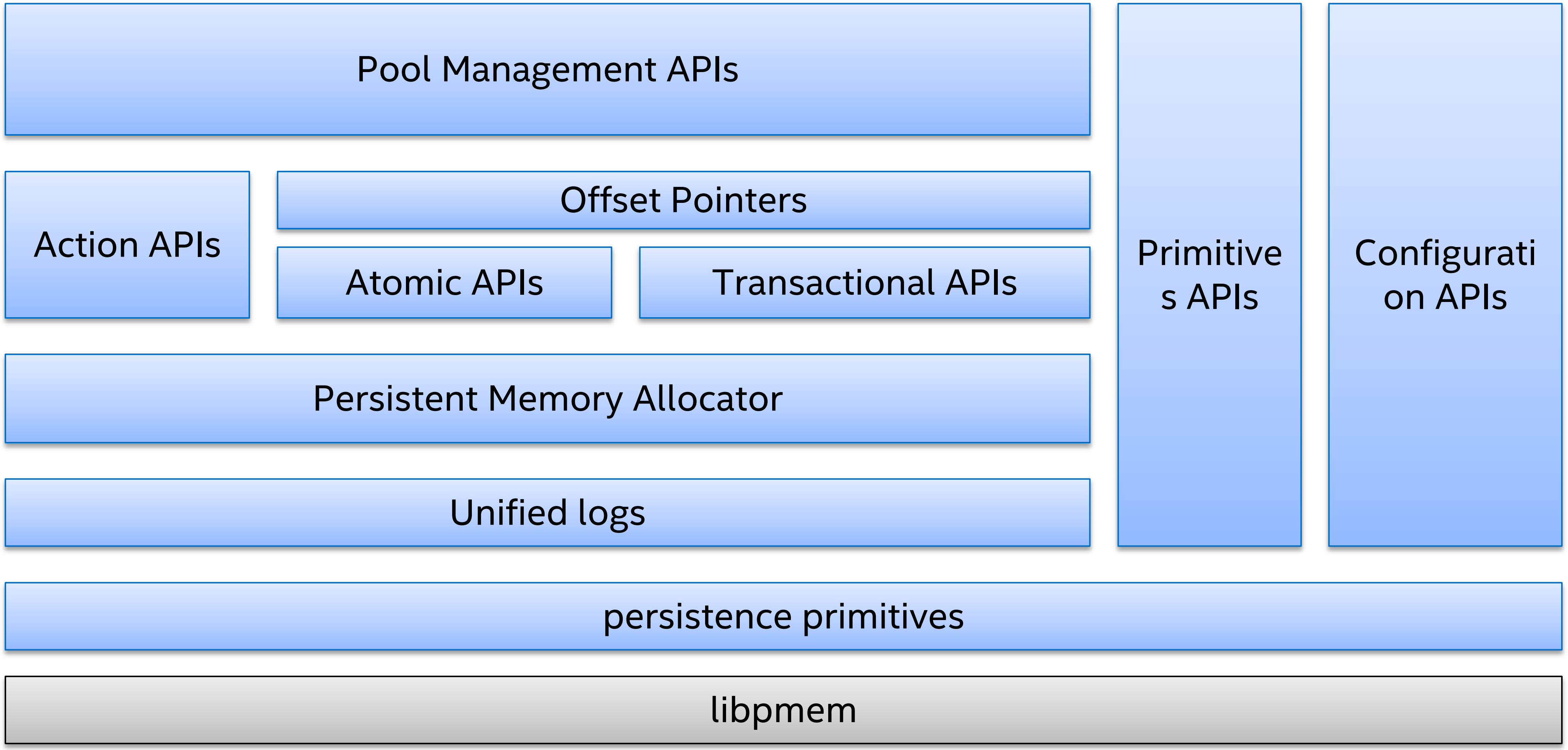
PMDK and libpmemobj

- http://pmem.io/
- open-source https://github.com/pmem
- vendor-agnostic
- user-space
- production quality, fully documented
- performance optimized and tuned

Software stack:

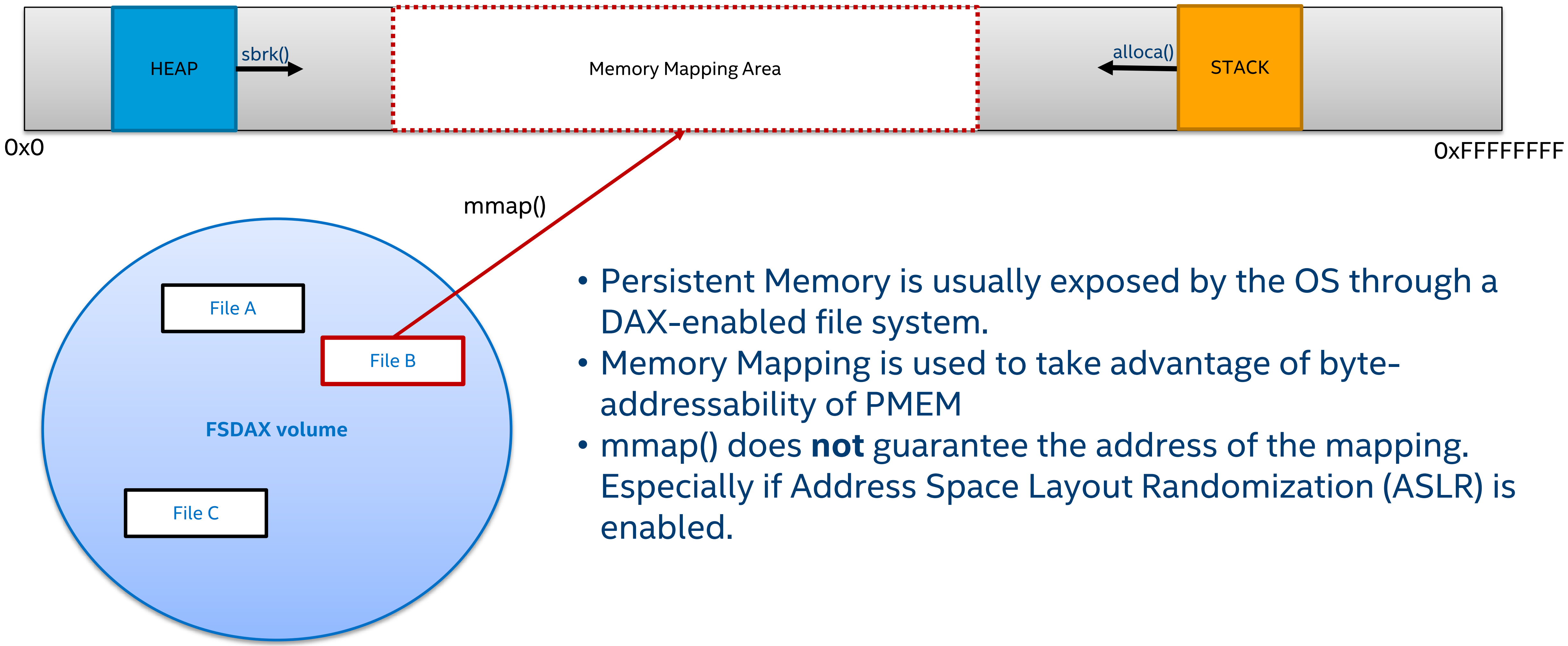

C++ idiomatic bindings for libpmemobj
libpmemobj++
Interface for persistent memory allocation, transactions and general facilities
libpmemobj
Low level support for local persistent memory
libpmem

libpmemobj


Pool Management APIs
Action APIs
Offset Pointers
Atomic APIs
Transactional APIs
Primitives APIs
Configuration APIs
Persistent Memory Allocator
Unified logs
persistence primitives
libpmem

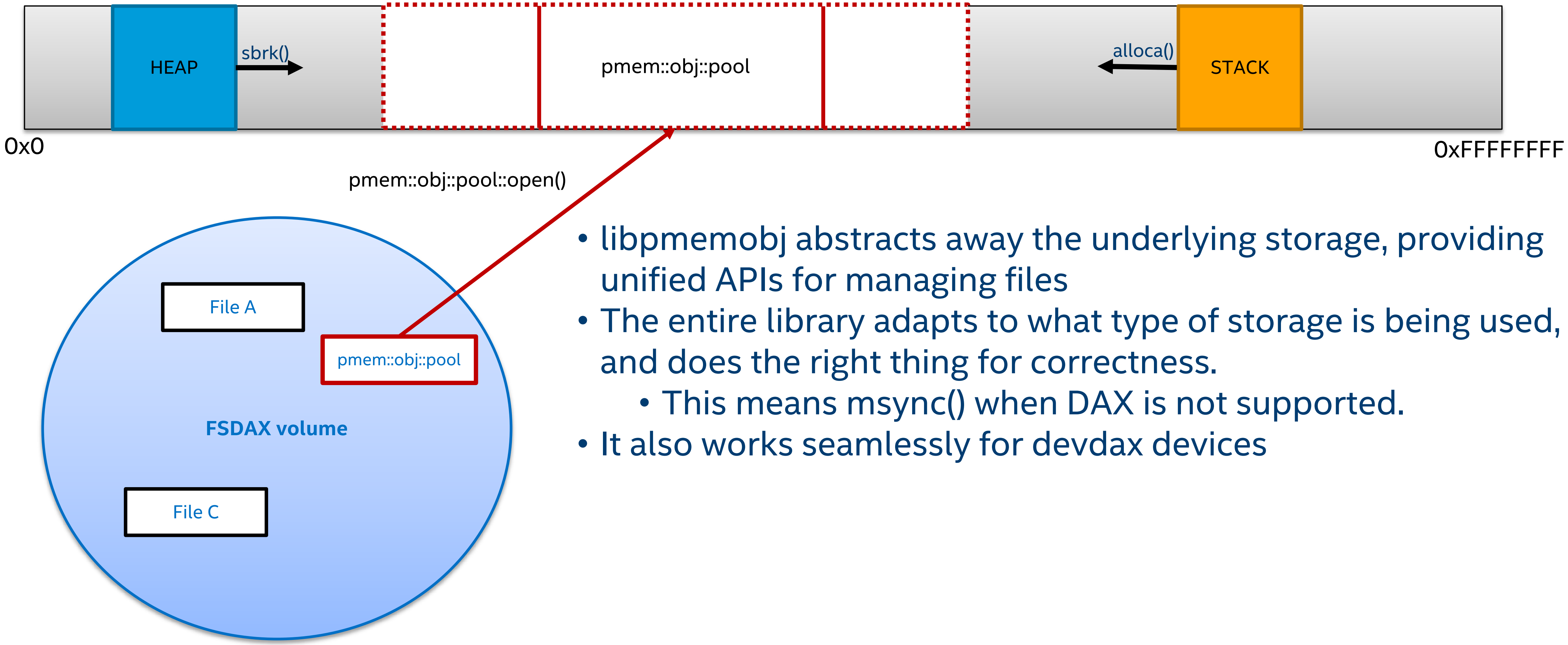
PERSISTENT MEMORY POOL

Pool Management APIs



- Persistent Memory is usually exposed by the OS through a DAX-enabled file system.
- Memory Mapping is used to take advantage of byte-addressability of PMEM
- mmap() does **not** guarantee the address of the mapping. Especially if Address Space Layout Randomization (ASLR) is enabled.

Pool Management APIs



- libpmemobj abstracts away the underlying storage, providing unified APIs for managing files
- The entire library adapts to what type of storage is being used, and does the right thing for correctness.
  - This means msync() when DAX is not supported.
- It also works seamlessly for devdax devices

http://pmem.io/libpmemobj-cpp/master/doxygen/classpmem_1_1obj_1_1pool.html

Pool Management APIs

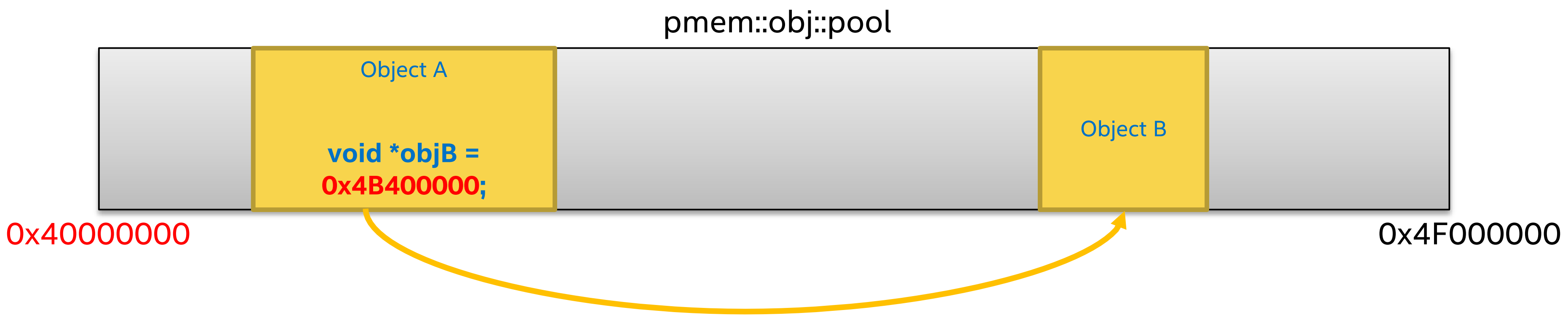
pool<> class example

```
if (access(path.c_str(), F_OK) != 0) {
    pop = pool<root>::create(path, "some_layout", PMEMOBJ_MIN_POOL, S_IRWXU);
} else {
    pop = pool<root>::open(path, "some_layout");
}
```

- Class template, where the template parameter is the type of the root object
- Supports basic operations
  - open – opens an existing pmempobj pool
  - create – creates a new pmemobj pool
  - close – closes an already opened/created pool
  - root – returns persistent pointer to root object associated with pool
- Inherits from pool_base

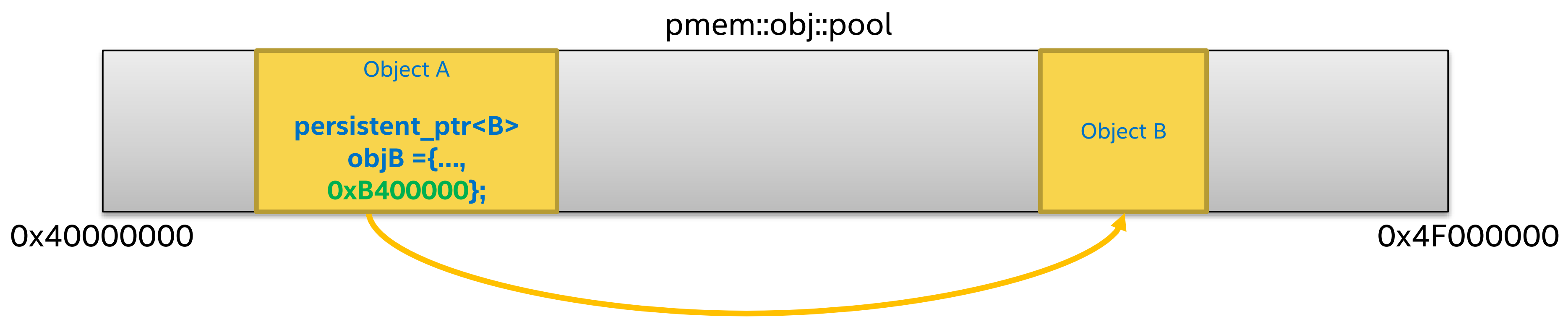
PERSISTENT POINTER

Persistent Pointer



- The base pointer of the mapping can change between application instances
- This means that any raw pointers between two memory locations can become invalid
- Must either fix all the pointers at the start of the application
    - Potentially terabytes of data to go through…
- Or use a custom data structure which isn't relative to the base pointer

Persistent Pointer

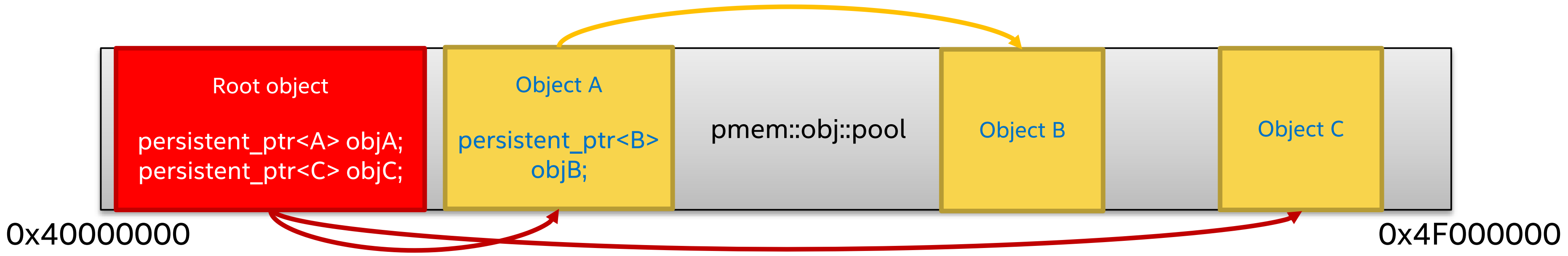


- libpmemobj provides 16 byte offset pointers, which contain an offset relative to the beginning of the mapping.
- Is a random access iterator
- Has primitives for flushing contents to persistence
- Does not manage object lifetime
- Does not automatically add contents to the transaction
- But it does add itself to the transaction

http://pmem.io/libpmemobj-cpp/master/doxygen/classpmem_1_1obj_1_1persistent__ptr.html

ROOT OBJECT

Root object



- All data structures of an application start at the root object.
- Has user-defined size, always exists and is initially zeroed.

- Applications should make sure that all objects are always reachable through some path that starts at the root object.
- Unreachable objects are effectively persistent memory leaks.

http://pmem.io/libpmemobj-cpp/master/doxygen/classpmem_1_1obj_1_1pool.html#a85b71b78e8229b009639835a5ad159d2

Root object

Retrieving root object from pool handle example

```
struct foo {
       persistent_ptr<bar> barp;
       long long x;
};

pop = pool<foo>::create(…);   // use “foo” type as a root

persistent_ptr<foo> r = pop.root();
assert(r->barp == nullptr);   // how to allocate an object of type “bar” in
                              // persistent memory?

r->x = 100;    // how to assign new value and guarantee data consistency?
               // What if crash happens during execution of this line?
```

TRANSACTIONS

Transactional API

- libpmemobj provides ACID (Atomicity, Consistency, Isolation, Durability) transactions for persistent memory
  - Atomicity means that a transaction either succeeds or fails completely
  - Consistency means that the transaction transforms `pmem::obj::pool` from one consistent state to another. This means that a pool won't get corrupted by a transaction.
  - Isolation means that transactions can be executed as if the operations were executed serially on the pool. This is optional, and requires user-provided locks.
  - Durability means that once a transaction is committed, it remains committed even in the case of system failures

Transactional API

Transaction example

```
auto pop = pool<root>::open("/path/to/poolfile", "layout string");

transaction::run(pop, [] {
    // do some work...
}, persistent_mtx, persistent_shmtx);
```

- Undo log based transactions
  - In case of interruption it is rolled-back or completed upon next pool open
- Take an `std::function` object as transaction body
- No explicit transaction commit
- Available with every C++11 compliant compiler
- Throw an exception when the transaction is aborted
- Take an arbitrary number of locks
- Can be nested

PMEM::OBJ::P

pmem::obj::p class

Code with manual snapshotting example

```
struct data {
    long long x;
}

auto pop = pool<data>::("/path/to/poolfile", "layout string");
auto datap = pop.root();

transaction::run(pop, [&]{
    pmemobj_tx_add_range(root, 0, sizeof (struct data));  // native C API
    datap->x = 5;
});
```

- If we won’t snapshot data and the crash will occur during execution of transaction, the old value of “x” field won’t be rolled-back

`pmem::obj::p` class

- Template class
- Overloads operator= for snapshotting in a transaction
- Overloads a bunch of other operators for seamless integration
  - Arithmetic
  - Logical
- Should be used for fundamental types
- No convenient way to access members of aggregate types
- No operator. to overload

pmem::obj::p class

Code with pmem::obj:p example

```
struct data {
    p<long long> x;
}

auto pop = pool<data>::("/path/to/poolfile", "layout string");
auto datap = pop.root();

transaction::run(pop, [&]{
    datap->x = 5;      // no need for implicit snapshotting
});
```

- More C++ idiomatic approach
- To modify your application and start using Persistent Memory, we should focus on modifying data structures, not functions

PERSISTENT MEMORY ALLOCATIONS

Persistent Memory allocations

- Can be used only within transactions
- Use transaction logic to enable allocation/delete rollback of persistent state
- make_persistent calls appropriate constructor
  - Syntax similar to std::make_shared
- delete_persistent calls the destructor
  - Not similar to anything found in std

Persistent Memory allocations

Transactional allocation example

```cpp
struct data {
    data(p<int> a, p<int> b) : a(a), b(b) {}
    p<int> a;
    p<int> b;
}
transaction::run(pop, [&]{
    persistent_ptr<data> ptr = make_persistent<data>(1, 2);
    assert(ptr->a == 1);
    assert(ptr->b == 2);

    // more code here

    delete_persistent<data>(ptr);
});
```

PERSISTENT MEMORY CONTAINERS

Persistent Memory containers

- compatible interface with STL counterparts (almost)
- Takes care of adding elements to a transaction
  - In operator[]/at() when obtainig non-const reference
  - On iterator dereference
  - In other methods which allow write access to data
- Works with std algorithms
- All functions which may alter container properties are atomic
  - This includes: resize(), reserve(), push_back() and others
  - Transactions are used internally
  - Strong exception guarantee
- Currently (libpmemobj++ 1.7) available containers:
  - array
  - vector
  - string (implemented basisc operations)
  - concurrent_hash_map (no STL counterpart, used as an engine for pmemkv)

Persistent Memory containers

vector usage example

```
transaction::run(pop, [&] {
        root->vec_p = make_persistent<vector<int>>();
});

vector_type &pvector = *(root->vec_p);

pvector.resize(10);
pvector = {5, 4, 3, 2, 1};
pvector.push_back(0);

transaction::run(pop, [&]{
    std::sort(pvector.begin(), pvector.end()); // 0,1,2,3,4,5

    delete_persistent<vector<int>>(ptr);
});
```

EXAMPLE

Example

volatile queue -> persistent queue

```
struct queue_node {
    int value;
    struct queue_node *next;
};

struct queue {
    …
    void
    push(int value)
    {
         auto node = new queue_node;
         node->value = value;
         node->next = nullptr;

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

```
struct queue_node {
    p<int> value;
    persistent_ptr<struct queue_node> next;
};

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

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

Example

volatile queue -> persistent queue

```
int
pop() {
    if (head == nullptr)
         throw std::out_of_range("no elements");

    auto head_ptr = head;
    auto value = head->value;

    head = head->next;
    delete head_ptr;

    if (head == nullptr)
         tail = nullptr;

    return value;
}

…
```

```
int
pop(pool_base &pop) {
    int value;
    transaction::run(pop, [&] {
    if (head == nullptr)
         throw std::out_of_range("no elements");

    auto head_ptr = head;
    value = head->value;

    head = head->next;
    delete_persistent<queue_node>(head_ptr);

    if (head == nullptr)
         tail = nullptr;
    });

    return value;
}

…
```

C++ STANDARD LIMITATIONS

C++ standard limitations

- Object lifetime begins when initialization is completed (constructor is called) and end when destructor calls starts
  - Similar problem to transmitting data over network (where the C++ application is given an array of bytes but might be able to recognize the type of object sent)
  - problem is well known and is being addressed by WG21 (The C++ Standards Committee Working Group)
  - For now, we must rely on undefined behavior
- Snapshotting – data is being copied with `memcpy()` and it means that we may break the inherent behavior of the object which may rely on the copy constructor
  - `std::is_trivially_copyable` should guarantee safe copying raw bytes, but is a restrictive type-trait (no user provided copy/move constructors)

C++ standard limitations

- Object layout:
  - might differ between compilers/compiler flags/ABI
  - compiler may do some layout-related optimizations and is free to shuffle order of members with same specifier type (public/protected/public)
  - No polimorfic types are allowed: there is no reliable and portable way to implement vtable rebuilding after reopening the pool

```
someType A = *reinterpret_cast<someType*>(mmap(...));
```

  - the bit representation of stored object type must be always the same and application should be able to retrieve stored object from memory mapped file without serialization.
  - `std::is_standard_layout` guarantee fixed layout, but is very restrictive type-trait

C++ standard limitations

- Storing volatile memory pointers in persistent memory is almost always a design error

```
class rootType {
        int* vptr;
}

...

int val = 1; /* variable on stack */
pmem::obj::transaction::run(pop, [&](){
        root->vptr = &val;
};);
```

- Using `pmem::obj::persistent_ptr<>` class template is safe, and it provides only way to access specific memory area after application crash
  - It doesn't satisfy requirements of `std::is_trivially_copyable` check
  - We rely on undefined behavior
- Type restrictions should not be a problem for native Persistent Memory applications – to fully utilize PMEM advantages, user should consider data oriented design principles

intel®

experience
what's inside™