# State of pmemkv

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# Agenda

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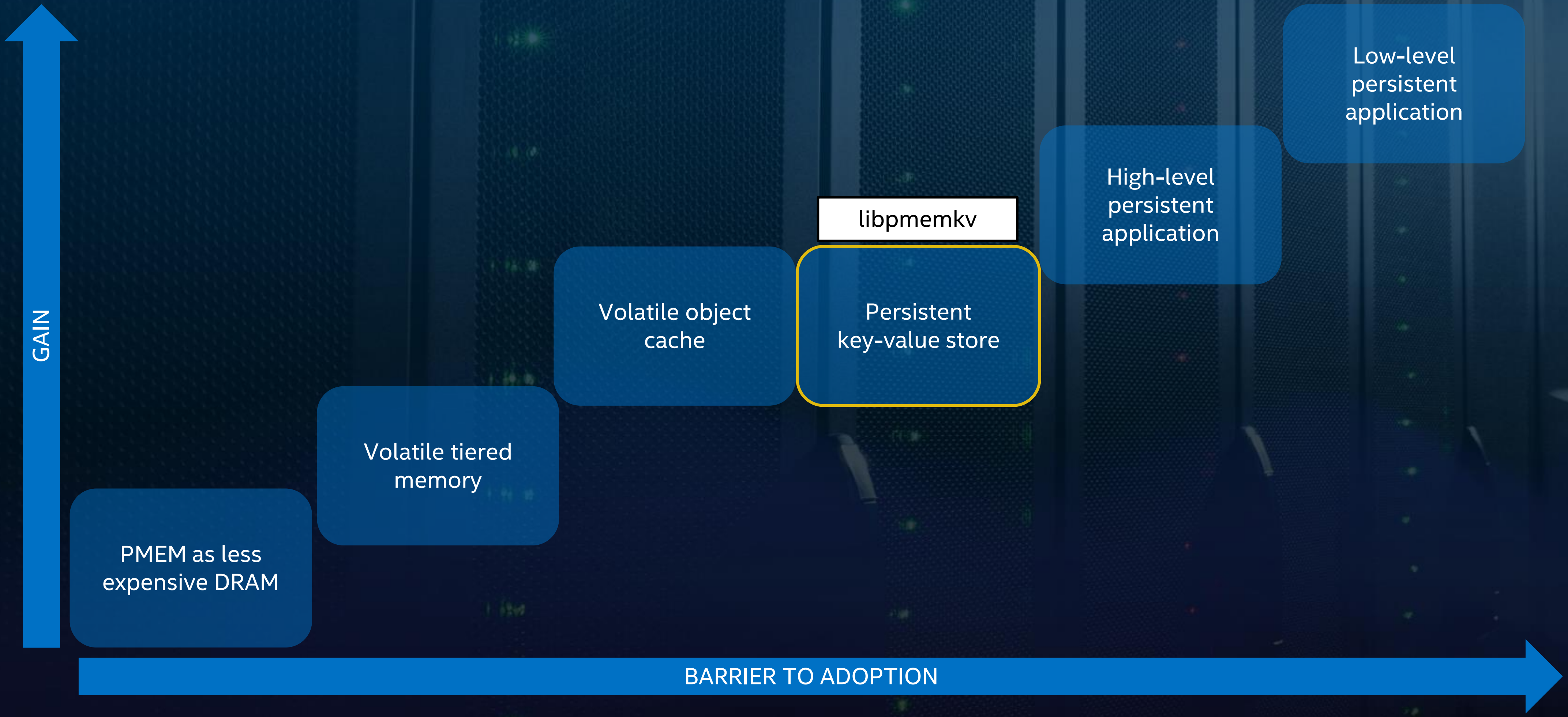
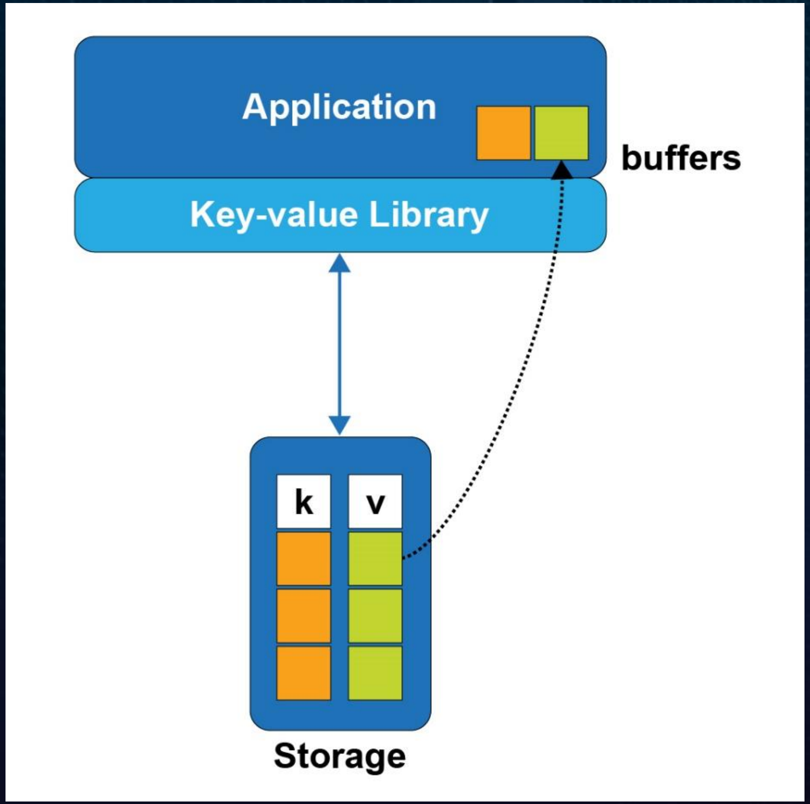
# Introduction to pmemkv

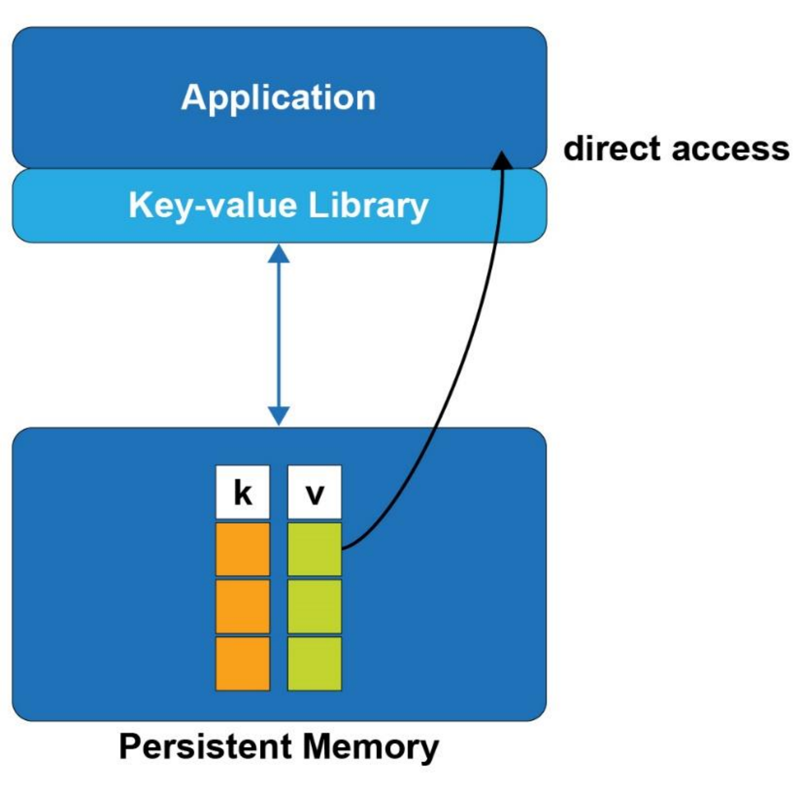
# WHY PMEMKV?


GAIN
PMEM as less expensive DRAM
Volatile tiered memory
Volatile object cache
libpmemkv
Persistent key-value store
High-level persistent application
Low-level persistent application
BARRIER TO ADOPTION

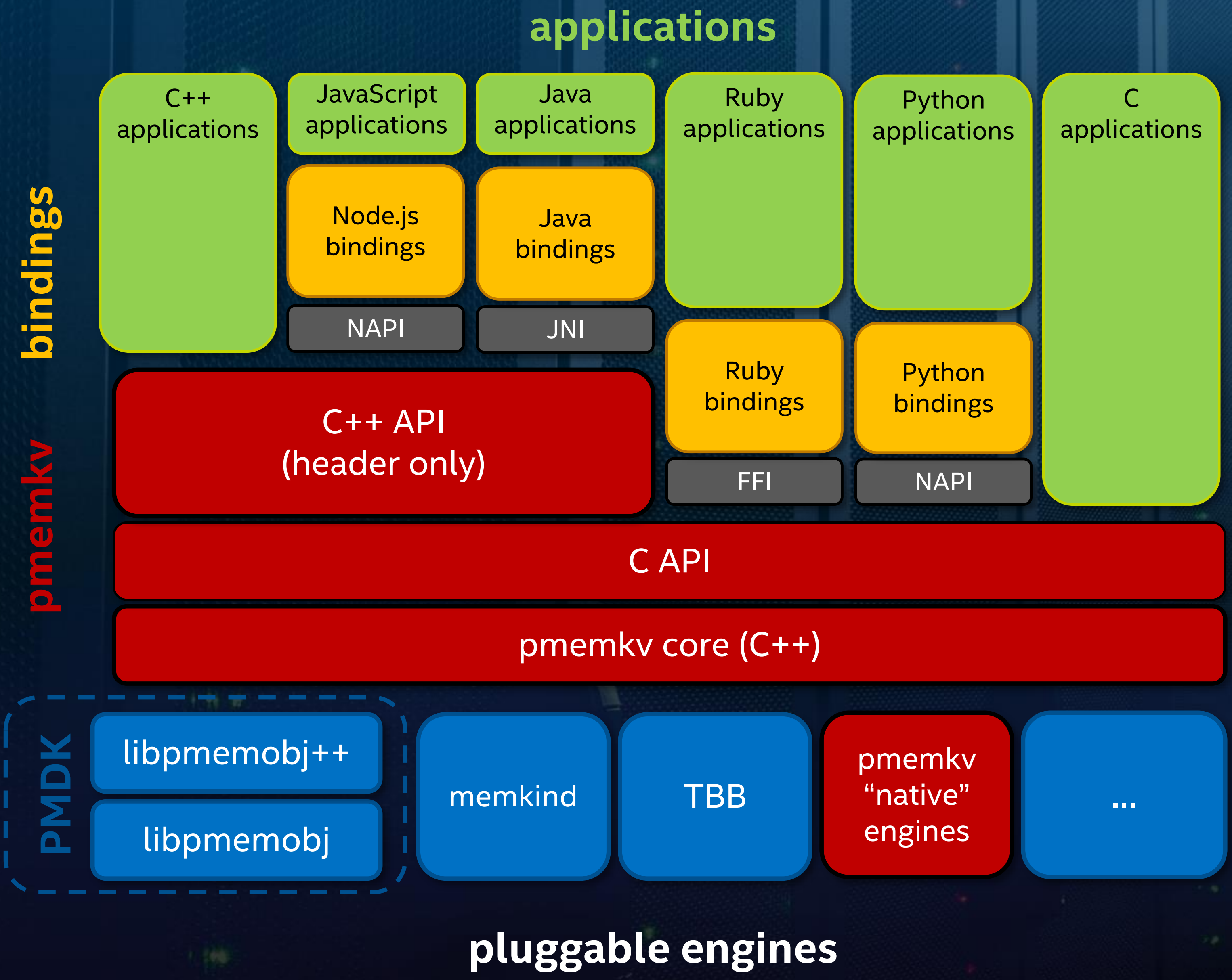
# WHY PMEMKV?

- Simple API allows to use persistent memory from high level languages
- Key-value store can take advantage from persistence and big capacity of Persistent Memory
- Key-value store can utilize Persistent Memory byte addressability
  - huge performance gain for relatively small keys and values



# DESIGN
Architecture



# ENGINES
Overview

| Engine Name | Description | Experimental | Concurrent | Sorted | Persistent |
|---|---|---|---|---|---|
| blackhole | Accepts everything, returns nothing | No (testing) | Yes | No | No |
| cmap | Concurrent hash map | No | Yes | No | Yes |
| vsmap | Volatile sorted hash map | No | No | Yes | No |
| vcmap | Volatile concurrent hash map | No | Yes | No | No |
| csmap | Concurrent sorted map | Yes | Yes | Yes | Yes |
| radix | Radix tree | Yes | No | Yes | Yes |
| tree3 | Persistent B+ tree | Yes | No | No | Yes |
| stree | Sorted persistent B+ tree | Yes | No | Yes | Yes |
| robinhood | Persistent hash map with Robin Hood hashing | Yes | Yes | No | Yes |
| dram_vcmap | Volatile concurrent hash map placed entirely on DRAM | Yes (testing) | Yes | No | No |

- Experimental engines are not yet a production quality (for various reasons) and their behavior may change. They are not included in build by default
- Test engines are delivered for benchmarking and testing reasons

# Pmemkv is simple!

# PMEMKV IS SIMPLE!

## API

Full API documentation (C / C++): https://pmem.io/pmemkv

- Well understood key-value API
  - Nothing new to learn
  - Inspired by RocksDB and LevelDB
- Life-cycle API
  - open() / close()
- Operations API
  - put(key, value)
  - get(key, value/v_callback)
  - remove(key)
  - exists(key)
- Other
  - errormsg()
- Iteration API
  - count_all()
  - get_all(kv_callback)
- +range versions of above (for ordered engines)
  - _below/_above/_between
- Iterators
- Transactions

# PMEMKV IS SIMPLE!

## C++ example – Database configuration

```
pmem::kv::config cfg;

pmem::kv::status s = cfg.put_path("/mnt/pmem0/MyDatabase.pool");
s = cfg.put_size(SIZE);
assert(s == status::OK);
s = cfg.put_create_if_missing(true);
assert(s == status::OK);

/* Opening pmemkv database with 'cmap' engine */
db kv = pmem::kv::db();
s = kv.open("cmap", std::move(cfg));
ASSERT(s == status::OK);
```

# PMEMKV IS SIMPLE!

## C++ example – Direct data access via lambda expressions

```
s = kv.put("key1", "value1");
assert(s == status::OK);
s = kv.put("key2", "value2");
assert(s == status::OK);

/* Access value directly on PMEM */
s = kv.get(("key1", [] (string_view v) {
    std::cout << v.data() << std::endl;
}
assert(s == status::OK);

/* Iterate over all key-value pairs directly on PMEM */
kv.get_all([](string_view k, string_view v) {
    std::cout << k.data() << " : " << c.data()<< std::endl;
    return 0;
});
s = kv.remove("key1");
assert(s == status::OK);
s = kv.exists("key1");
assert(s == status::NOT_FOUND);
```

# PMEMKV IS SIMPLE!

## C++ example – Direct data access via Iterators

- Experimental API
- read and write iterators
- Cannot hold simultaneously in the same thread more than one iterator.
- Holds lock per element

```cpp
auto res_w_it = kv->new_write_iterator();
assert(res_w_it.is_ok());
auto &w_it = res_w_it.get_value();
/* seek to the element lower than "5" */
status s = w_it.seek_lower("5");
assert(s == status::OK);
do {
    std::string value_before_write =
    w_it.read_range().get_value().data();

    auto res = w_it.write_range();
    assert(res.is_ok());
    for (auto &c : res.get_value()) {
        c = 'x';
    }
    w_it.commit();
} while (w_it.next() == status::OK);
```

# PMEMKV IS SIMPLE!

## C++ example – Transactions API, and why we need it?

- Experimental API
- Allows grouping put/get/remove into single atomic action
- Provides ACID properties (no isolation for single threaded engines)

```
auto result_tx = kv.tx_begin();
assert(result_tx.is_ok());

/* This function is guaranteed to not throw if is_ok is true */
auto &tx = result_tx.get_value();
s = tx.remove("key1");
s = tx.put("key2", "value2");

/* Until transaction is committed, changes are not visible */
assert(kv.exists("key1") == status::OK);
assert(kv.exists("key2") == status::NOT_FOUND);

s = tx.commit();
assert(s == status::OK);

assert(kv.exists("key1") == status::NOT_FOUND);
assert(kv.exists("key2") == status::OK);
```

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# Language bindings

# LANGUAGE BINDINGS

Simple API = easy to implement high-level language bindings with small performance overhead

- Currently 4 available language bindings for pmemkv:
  - Java (v. 1.0.1) https://github.com/pmem/pmemkv-java
  - Python (v. 1.0) https://github.com/pmem/pmemkv-python
  - NodeJS (v. 1.0) https://github.com/pmem/pmemkv-nodejs
  - Ruby (v. 0.9) https://github.com/pmem/pmemkv-ruby

- Their APIs are designed to fit into languages common practices

# LANGUAGE BINDINGS
## Python and Java example

```python
import pmemkv
# Configuration dictionary
config = { "path":"/dev/shm",
           "size":1073741824 }

db = pmemkv.Database("vsmap", config)

db.put("key1", "value1")

# Get single value and key in lambda
expression

key = "key1" db.get(
    key,
    lambda v, k=key: print(
         f"key: {k} with value: "      I
        if"{memoryview(v).tobytes().decode()}"
        ), )

db.stop();
```

```java
Database<String, String> db =
  new Database.Builder<String, String>(ENGINE)
       .setSize(1073741824)
       .setPath("/dev/shm")
       .setKeyConverter(new StringConverter())
       .setValueConverter(new StringConverter())
       .build();

db.put("key1", "value1");
assert db.countAll() == 1;

assert db.getCopy("key1").equals("value1");

// Iterating existing keys
db.getKeys((k) ->
        System.out.println("  visited: " + k));
db.stop();
```

# PERFORMANCE MEASUREMENTS

- pmemkv_bench is a separate GitHub repository with benchmark tool inspired by db_bench

  https://github.com/pmem/pmemkv-bench

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# Technical overview

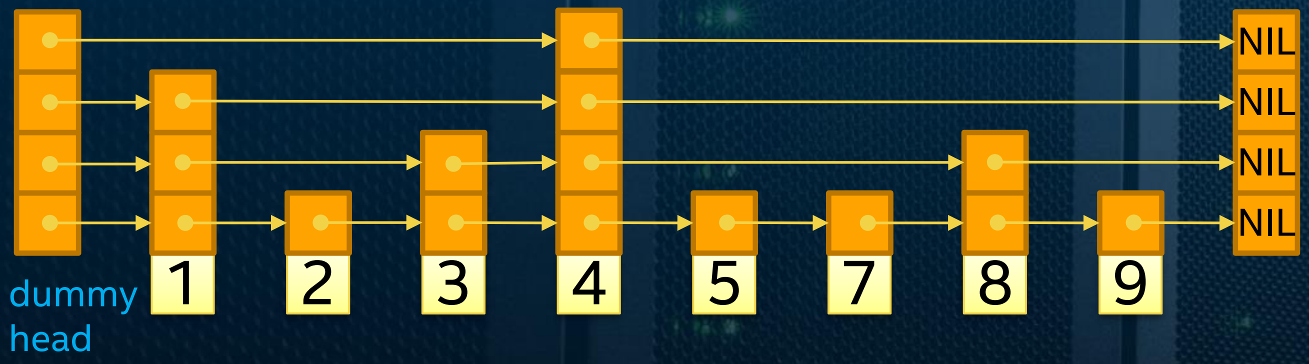
# LIBPMEMOBJ-CPP (BASE FOR PMEMKV ENGINES)

Transactional object store for Persistent Memory. It provides:

- ACID transactions
- Failure-atomic allocator
- General facilities useful for Persistent Memory programming
- Data structures optimized fo Persistent Memory
  - Vector, String, Array, Segment vector
  - Concurrent_map, Concurrent_hash_map
  - Radix tree

https://www.cs.tau.ac.il/~shanir/nir-pubs-web/Papers/OPODIS2006-BA.pdf

# CSMAP: CONCURRENT SKIP LIST




| Algorithm | Average | Worst |
|---|---|---|
| Space | O(n) | O(n log n) |
| Search | O(log n) | O(n) |
| Insert | O(log n) | O(n) |
| Delete | O(log n) | O(n) |

- Multilayer linked list-like data structure.
  - The bottom layer is an ordinary ordered linked list.
  - Each higher layer acts as an "express lane" for the lists below.
- An element in layer i appears in layer i+1 with fixed probability p (in our case p = 1/2).
- Search is wait-free.
- Insert employs optimistic lock-based synchronization.

# CSMAP: DELETE OPERATION

Our implementation does not support concurrent delete operation

- There is a way to logically delete a node from the skip list. But…
- There is a memory reclamation problem
  - We need to guarantee object life-time, while other threads accessing it
  - It is hard to solve without garbage collector
- There are possible solutions, but they might hurt Search/Insert performance
  - Hazard pointers
  - Epoch-based reclamation

# PMEMKV PROPERTIES AND TESTING

- Properties:
  - Atomic inserts/updates/removes
  - Read guarantees (only commited data can be read)
  - No persistent memory leaks
- Testing:
  - pmemcheck
  - pmreorder

# DATA CONSISTENCY IN CONCURRENT LIST-LIKE DATA STRUCTURES (INSERT)

```
{
    manual tx;

    // allocate new node
    auto ptr = make_persistent(...);

    // insert node to the list
    atomic_store(list->next, ptr);

// other threads will see uncomitted state

    commit();
}
```

- Cannot easily use atomic instruction within a transaction

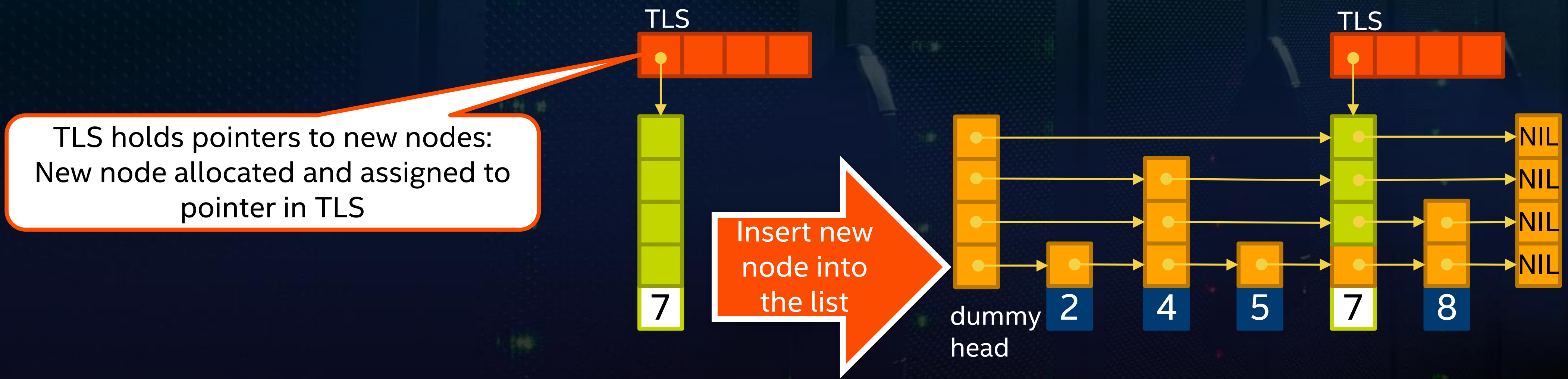
# DATA CONSISTENCY IN CONCURRENT LIST-LIKE DATA STRUCTURES (INSERT)

```
persistent_ptr ptr; // ptr resides on-stack

{
    manual tx;
    ptr = make_persistent(...);
    commit();
}

// Memory leak, if a crash happens here

atomic_store(list->next, ptr);
persist(list->next);
```

- All nodes must be reachable after restart

# DATA CONSISTENCY IN CONCURRENT LIST-LIKE DATA STRUCTURES

- Data consistency = each node is reachable after crash
- Use persistent TLS to track persistent allocations
- Each new node is always reachable via TLS
  - In case of a crash, we can redo insert if it was not completed



# DATA CONSISTENCY IN CONCURRENT LIST-LIKE DATA STRUCTURES (INSERT)

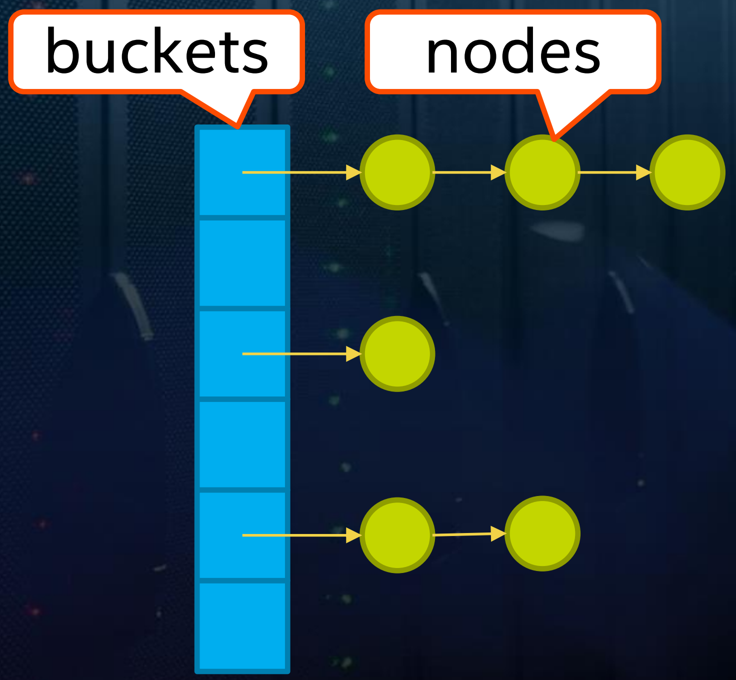
```
auto &ptls = persistent_tls.local();

{
    manual tx;
    ptls.ptr = make_persistent();
    commit();
}

atomic_store(list->next, ptls.ptr);
persist(list->next);
```

- Use Persistent TLS to avoid memory leak
- On restart, all not inserted nodes are reachable through Persistent TLS

# CMAP: CONCURRENT HASH MAP

- Optimistic per-bucket Read-Write lock
  - Find() acquires read lock
  - Insert() and Erase() acquires write lock
- Each operations do following actions:
  - Finds required bucket using the hash
  - Lock the bucket for read or write access
  - Isolation: only a single writing thread can modify bucket at a time
  - Works with the nodes inside bucket

| Algorithm | Average | Worst |
|---|---|---|
| Space | O(n) | O(n) |
| Search | O(1) | O(n) |
| Insert | O(1) | O(n) |
| Delete | O(1) | O(n) |



# LOCKS ON PMEM

```
struct hash_map_node {
    ...
    /** Next node in chain. */
    node_ptr_t next;

    /** Mutex (wrapper around pthread_mutex_t) */
    mutex_t mutex;

    /** Item stored in node */
    value_type item;
};
```

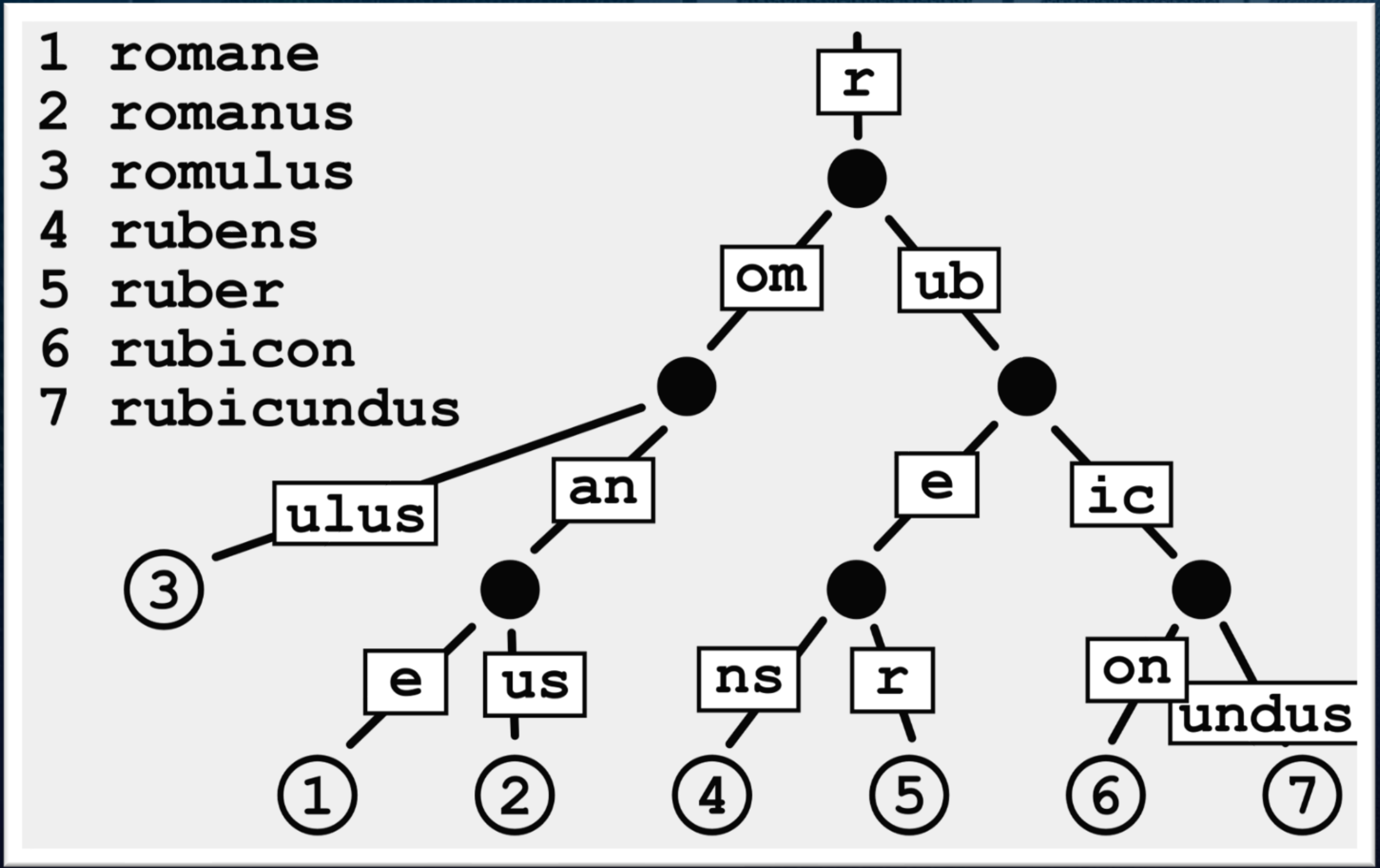
- Locking/unlocking = writing to pmem
- No explicit flush but cache lines are invalidated when accessed from different cores
- Affects cmap, csmap, vcmap

# MOVING LOCKS TO DRAM

- Use sharding instead of per-element lock
- Keep per-element locks in DRAM (pointer to lock on PMEM)
  - Feasible for large elements
  - Possible with pmem::obj::concurrent_hash_map and tbb::concurrent_hash_map

```
template <typename Key, typename T,
          typename HashCompare = d1::tbb_hash_compare<Key>,
          typename Allocator = tbb_allocator<std::pair<const Key, T>>
#if __TBB_PREVIEW_CONCURRENT_HASH_MAP_EXTENSIONS
        , typename MutexType = spin_rw_mutex
#endif
         >
class concurrent_hash_map
```

# RADIX TREE – BRIEF DESCRIPTION




https://en.wikipedia.org/wiki/Radix_tree#/media/File:Patricia_trie.svg

# RADIX TREE

- Persistent, single threaded, sorted engine
- Implementation avaialable in libpmemobj-cpp as container with std::map compatible API
- No key comparisons (less reads from pmem)
- No costly rebalancing
- Supports inline_string

# REDUCING NUMBER OF ALLOCATIONS WITH INLINE_STRING

```
radix_tree<pmem::obj::string, int> r;

...

r.try_emplace("some very long string ...",
              1); // two allocations
```

root

```
struct leaf {
    ...
    pmem::obj::string key;
    int value = 1;
};
```

„some very long string ...”

# REDUCING NUMBER OF ALLOCATIONS WITH INLINE_STRING

```
radix_tree<pmem::obj::inline_string, int> r;

...

r.try_emplace("some very long string ...",
              1); // one allocation
```

root

```
struct leaf {
    ...
};
```

```
struct inline_string {
    size_t size;
    size_t capacity;
};
```

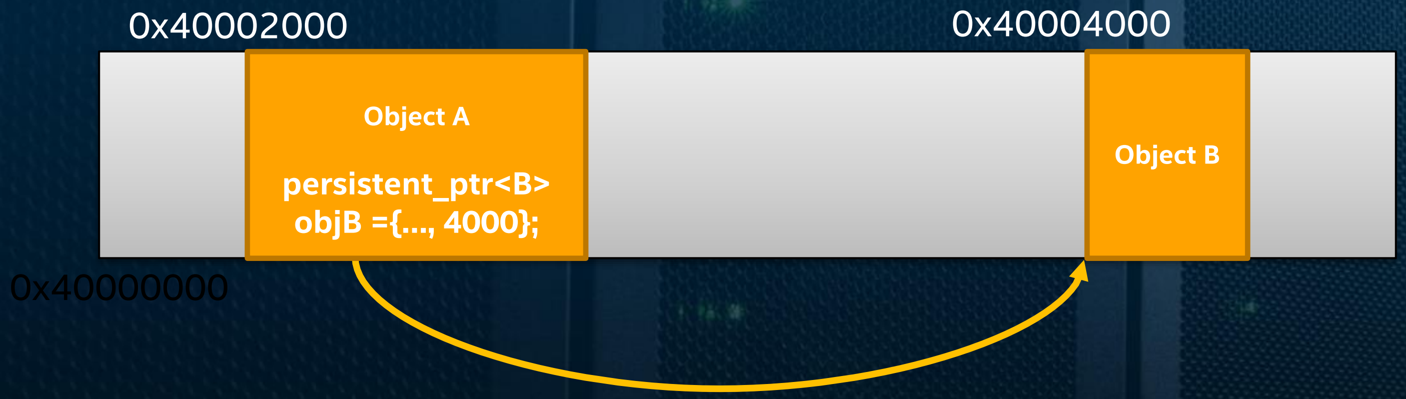
„some very long string ...”

int value = 1

# ROBINHOOD

- Persistent, concurrent, unsorted engine
- Supports 8B keys and values only
- Uses robinhood hashing: variant of open addressing
- Cache friendly and memory efficient
- Concurrency achieved through sharding

# PMEM::OBJ::PERSISTENT_PTR PERFORMANCE PROBLEM

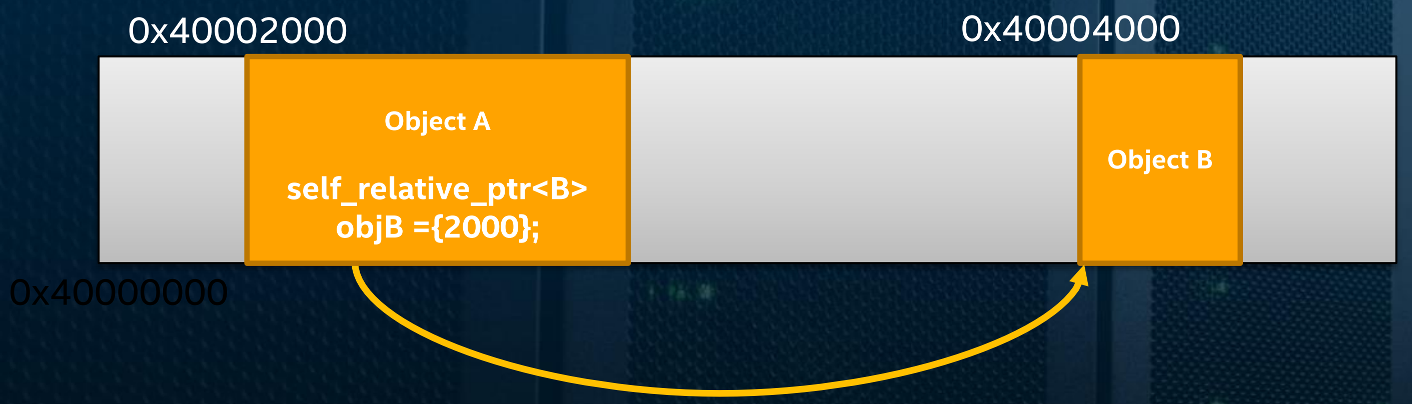



```
typedef struct pmemoid {
   uint64_t pool_uuid_lo;
   uint64_t off;
} PMEMoid;

void* pmemobj_direct(PMEMoid oid) {
    if (cache->uuid_lo != oid.pool_uuid_lo) {
        cache->pop = pmemobj_pool_by_oid(oid);
        cache->uuid_lo = oid.pool_uuid_lo;
    }
    return (void *)((uintptr_t)cache->pop + oid.off);
}
```

Cached in TLS

- Compiler cannot optimize access to cache->pop
- Each pointer derefence goes through tls

# PMEM::OBJ::SELF_RELATIVE_PTR




- No caching needed
- Size of self_relative_ptr is 8B
- Provides std::atomic specialization

```
T* self_relative_ptr::get() {
    if (is_null())
        return nullptr;
    return reinterpret_cast<byte_ptr_type>(const_cast<this_type *>(this)) + offset + 1;
}
```

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# Future plans

# FUTURE PLANS

- Combining radix with a DRAM caching layer

Write (K5, V5)

DRAM index (cache)

{…}, {…}, {K5, V5}

pmem log

| … | … | K5, V5 |

Send message to Thread 3 to insert (K5, V5)

| Thread 1 | Thread 2 | Thread 3 |
|---|---|---|

SHARDED RADIX

# FUTURE PLANS

- Allowing single writer and multiple readers (lock-free) for radix
  - Epoch-based reclamation
- Extending bindings functionality
- Optimizing existing engines
- Publishing regular performance reports
- Pmemkv client for YCSB
- Creating more educational materials about data structure design

# CALL TO ACTION

- Read more about persistent memory and concurrent data structures
  - https://pmem.io/book/
- Try our data structures
  - https://github.com/pmem/libpmemobj-cpp
- Try PMEMKV in your C/C++, Java, Python or NodeJS apps
  - https://github.com/pmem/pmemkv
- Learn more about concurrency in failure atomic data structures
  - https://www.youtube.com/watch?v=6V5LcBKhpJE&t=1659s

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