

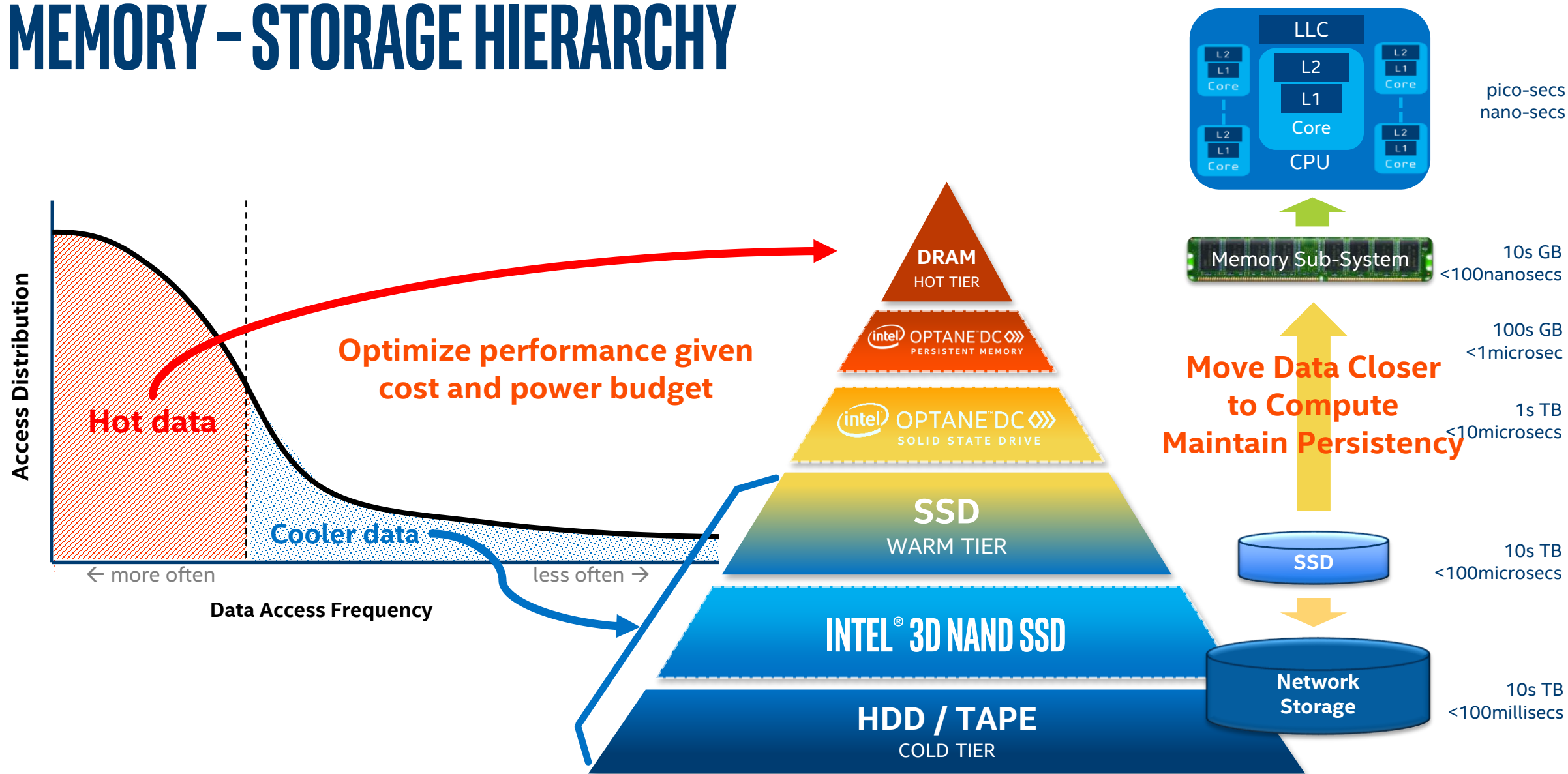


INTRODUCTION TO PROGRAMMING FOR PERSISTENT MEMORY

AGENDA

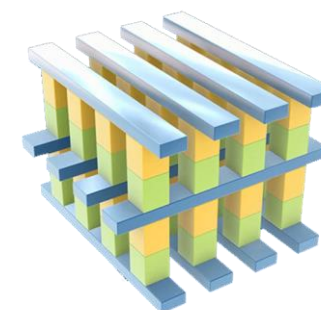
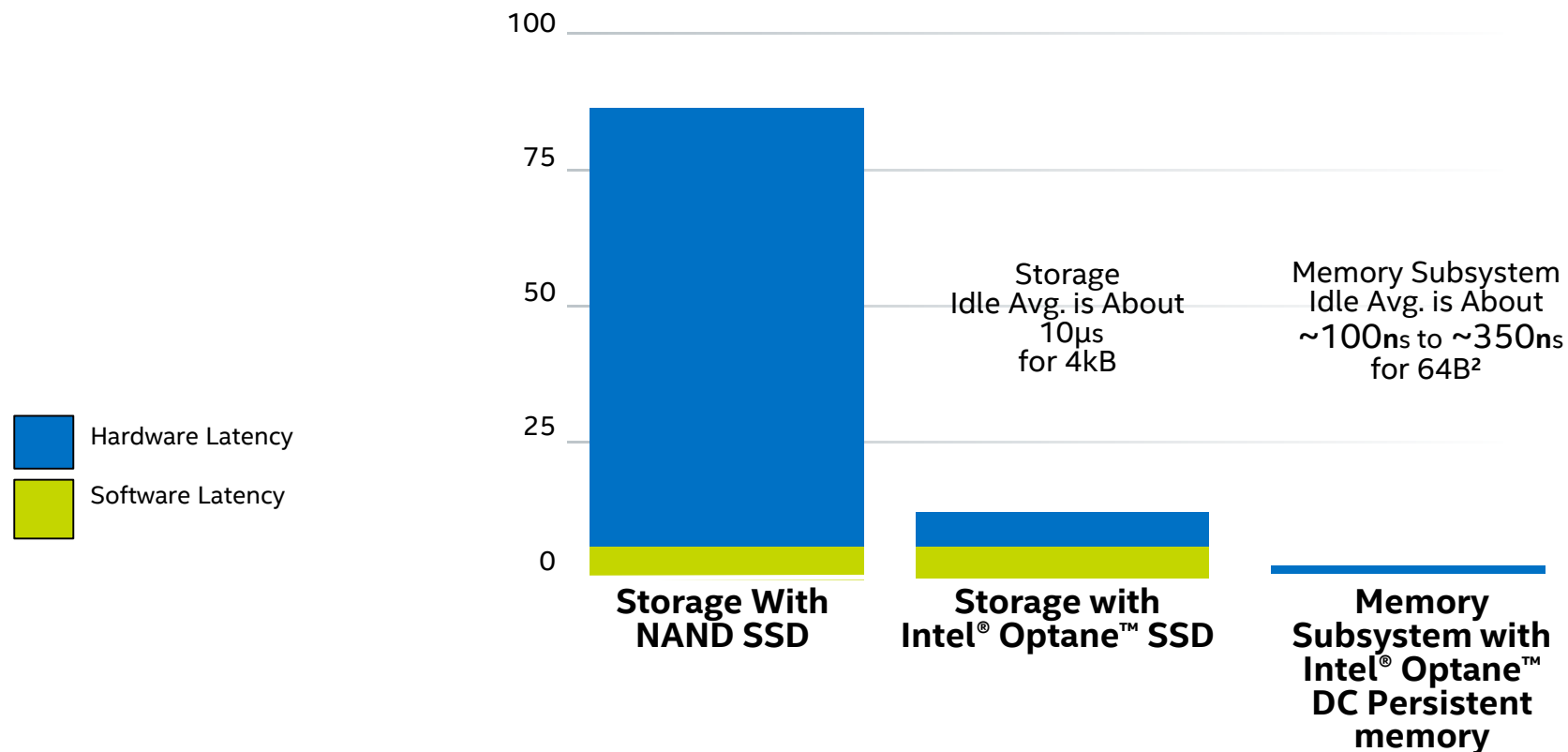
- Memory - Storage hierarchy
- What is Persistent Memory?
- Persistent Memory usage modes
- SNIA NVM Programming Model
- Application responsibilities:
 - Understanding power-failure atomicity
 - Persistence domain
 - Visibility versus Power Fail Atomicity

MEMORY - STORAGE HIERARCHY



MEMORY – STORAGE HIERARCHY

Idle Average Random Read Latency¹



¹ Source: Intel-tested: Average read latency measured at queue depth 1 during 4k random write workload. Measured using FIO 3.1. comparing Intel Reference platform with Optane™ SSD DC P4800X 375GB and Intel® SSD DC P4600 1.6TB compared to SSDs commercially available as of July 1, 2018. Performance results are based on testing as of July 24, 2018 and may not reflect all publicly available security updates. See configuration disclosure for details. No product can be absolutely secure. For more complete information about performance and benchmark results, visit www.intel.com/benchmarks.

² App Direct Mode, NeonCity, LBG B1 chipset, CLX B0 28 Core (QDF QQYZ), Memory Conf 192GB DDR4 (per socket) DDR 2666 MT/s, Optane DCPMM 128GB, BIOS 561.D09, BKC version WW48.5 BKC, Linux OS 4.18.8-100.fc27, Spectre/Meltdown Patched (1,2,3, 3a)

LATENCY AT HUMAN SCALE

System Event	Actual Latency	Scaled Latency
One CPU cycle	0.4 ns (1 cycle)	1 s
Level 1 cache access	2 ns (5 cycles)	5 s
Level 2 cache access	4.8 ns (12 cycles)	12 s
Level 3 cache access	26 ns (65 cycles)	1 min 5sec
Main memory access (DDR DIMM)	<100 ns	4 min 10sec
NVDIMM-N memory access	<100 ns	4 min 10sec
Intel Optane DC Persistent Memory access	<100-300 ns	4 min 10sec - 12 min
Intel Optane DC SSD I/O P4800X NVMe	~10 µs	~7hrs
NVMe SSD I/O	~25 µs	17 hrs 21min
SSD I/O	50–150 µs	1 day 11hrs – 4 days, 8hrs
Rotational disk I/O	1–10 ms	28 days 22hrs – 289 days
Tape	~100ms	7 yrs 11 months

From “Systems Performance: Enterprise and the Cloud”, Brendan Gregg

WHAT IS PERSISTENT MEMORY?

- Byte or block addressable
- load/store memory access
- persistence properties of storage

JEDEC NVDIMM Standards			
	NVDIMM-F	NVDIMM-N	NVDIMM-P
IO Access Methods	Block	Block or Byte	Block or Byte
Capacity	100's GB – 1's TB	1's - 10's GB	100's GB – 1's TB
Latency	<50us	<100ns	<300ns
First Availability	2014	2016	2019
Operating System Support	Linux Kernel x.x Windows?	Linux Kernel >4.0 Windows Server 2016	Linux Kernel >4.2 Windows Server 2019

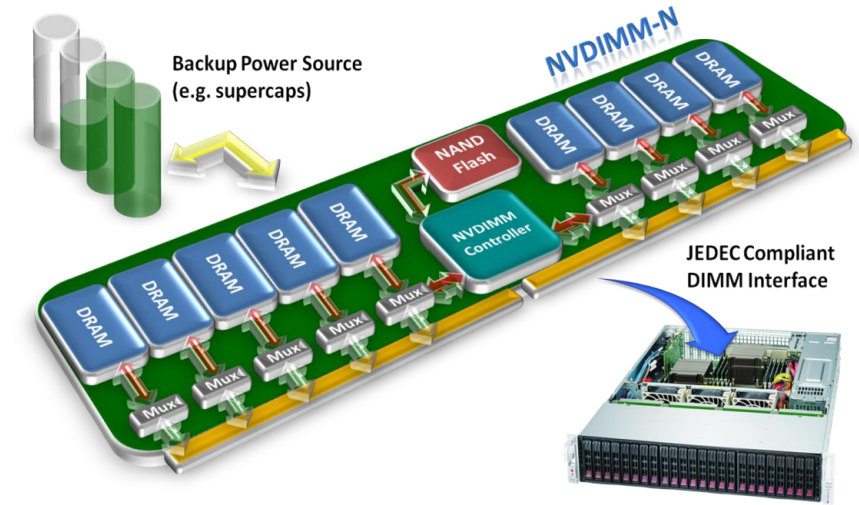
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intel[®] OPTANE™ DC

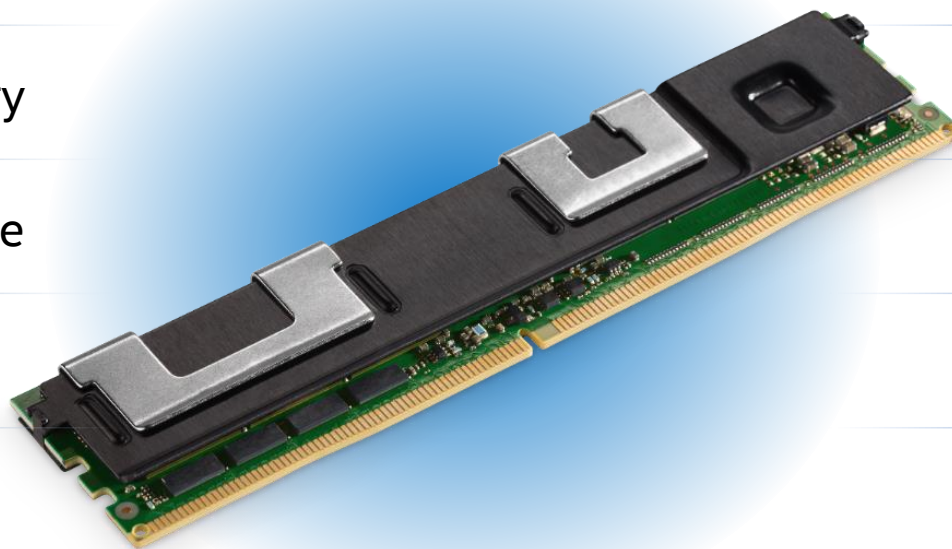
PERSISTENT MEMORY

Big and Affordable Memory

Highest Performance Storage

Direct Load/Store Access

Native Persistence



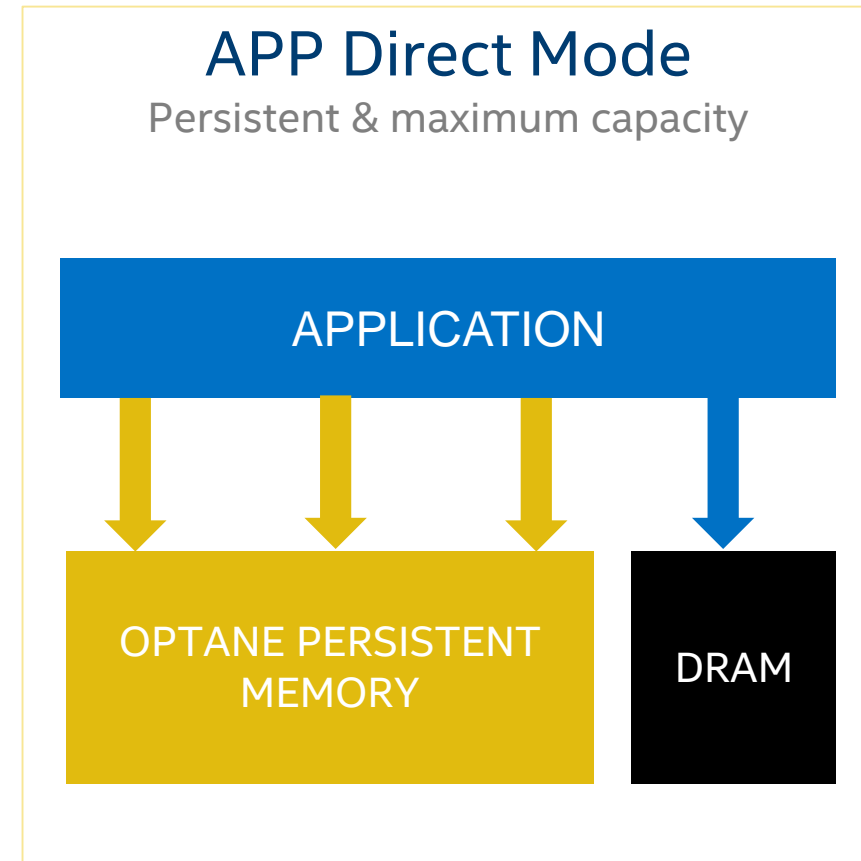
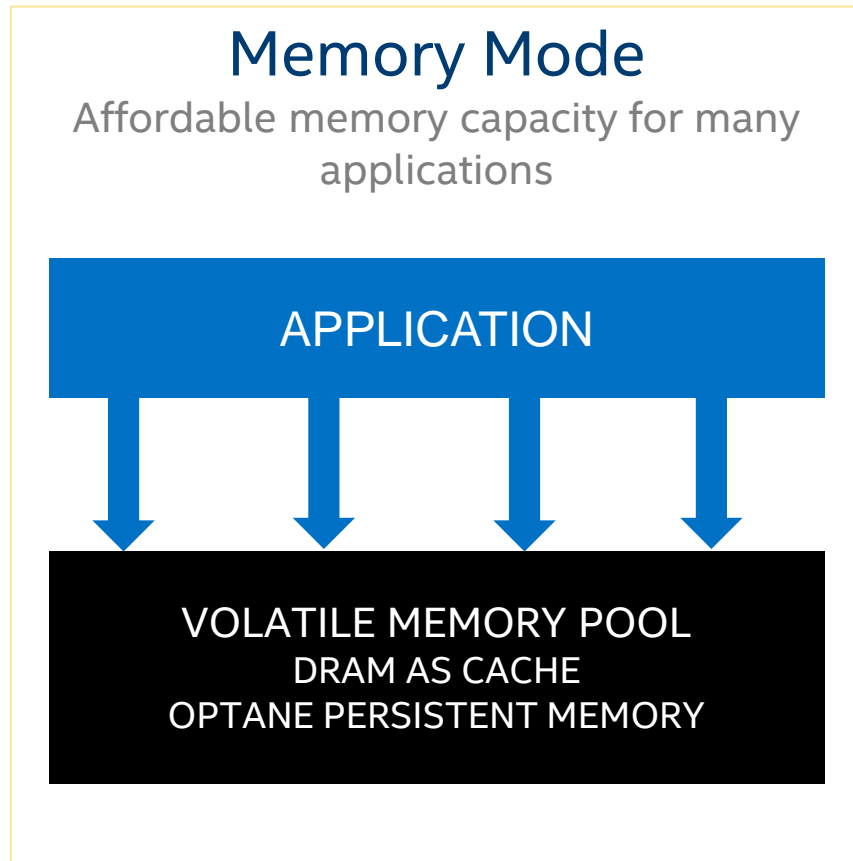
128, 256, 512GB

DDR4 Pin Compatible

Hardware Encryption

High Reliability

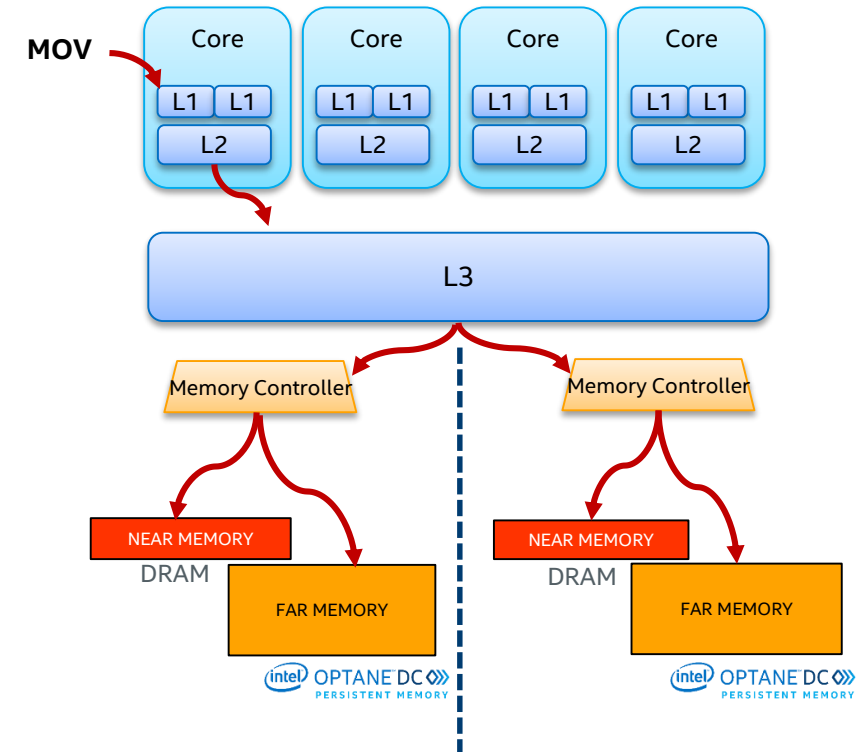
PERSISTENT MEMORY USAGE MODES



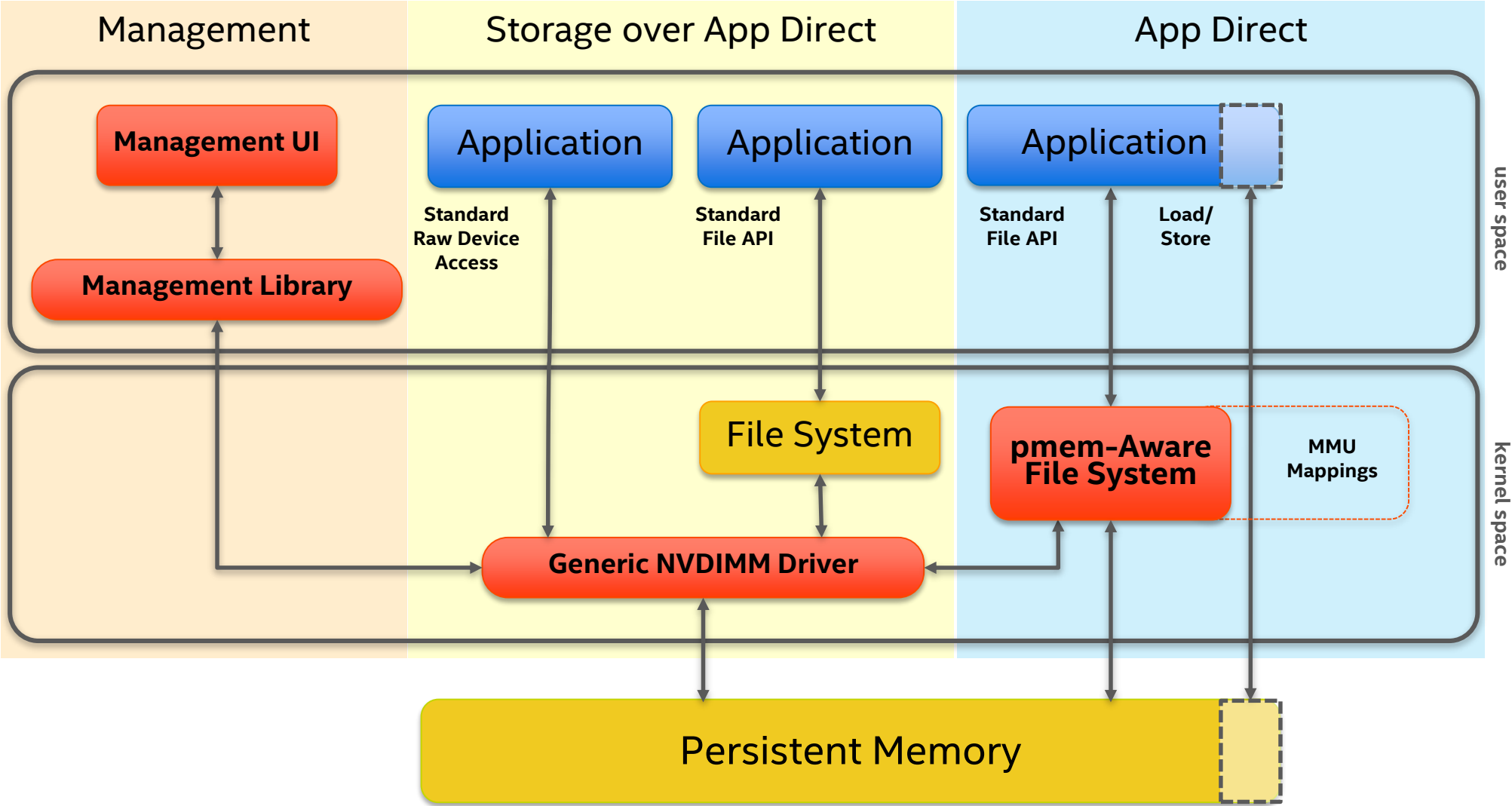
PERSISTENT MEMORY USAGE MODES

Memory Mode details

- No software/application changes required
- To mimic traditional memory, data is “volatile”
 - Volatile mode key cleared and regenerated every power cycle
- DRAM is “near memory”
- Used as a write-back cache
- Managed by host memory controller
- Within the same host memory controller, not across
- Ratio of far/near memory (PMEM/DRAM) can vary
- Overall latency
- Same as DRAM for cache hit
- Intel® Optane™ DC persistent memory + DRAM for cache miss



SNIA NVM PROGRAMMING MODEL

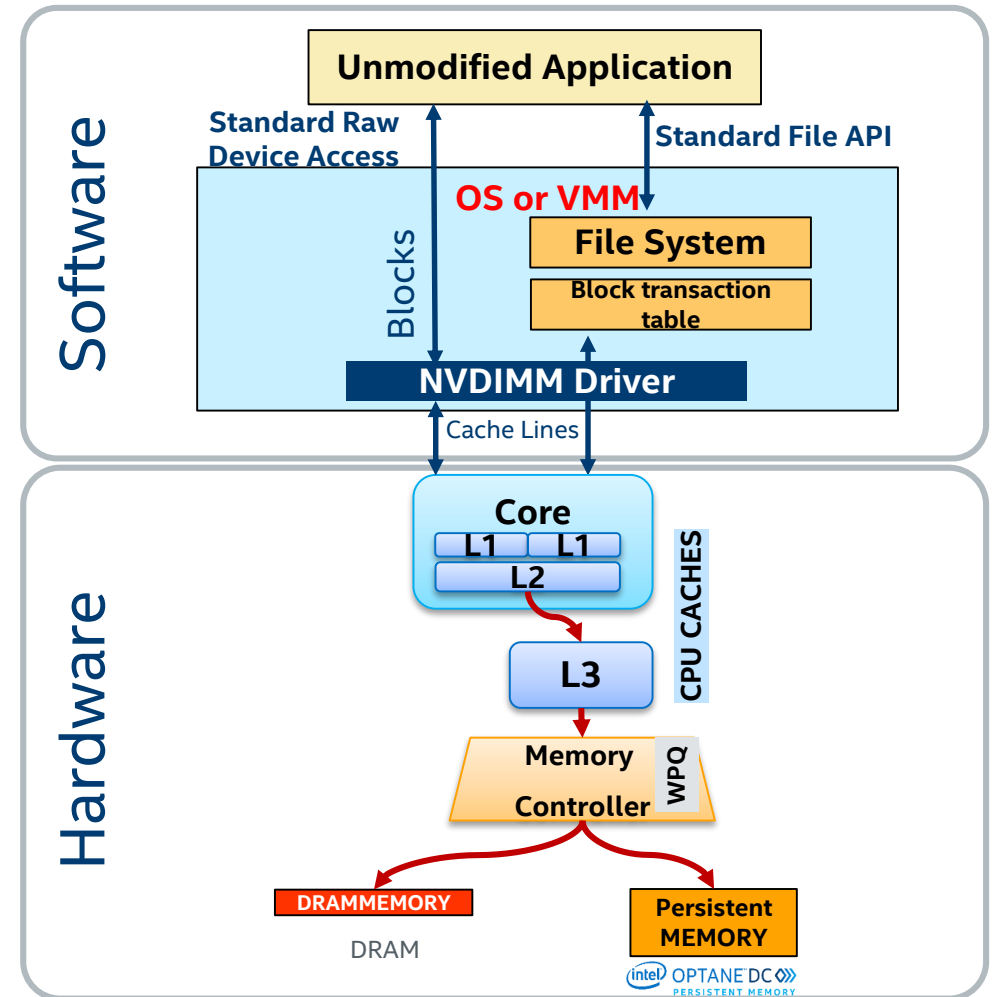


PERSISTENT MEMORY USAGE MODES

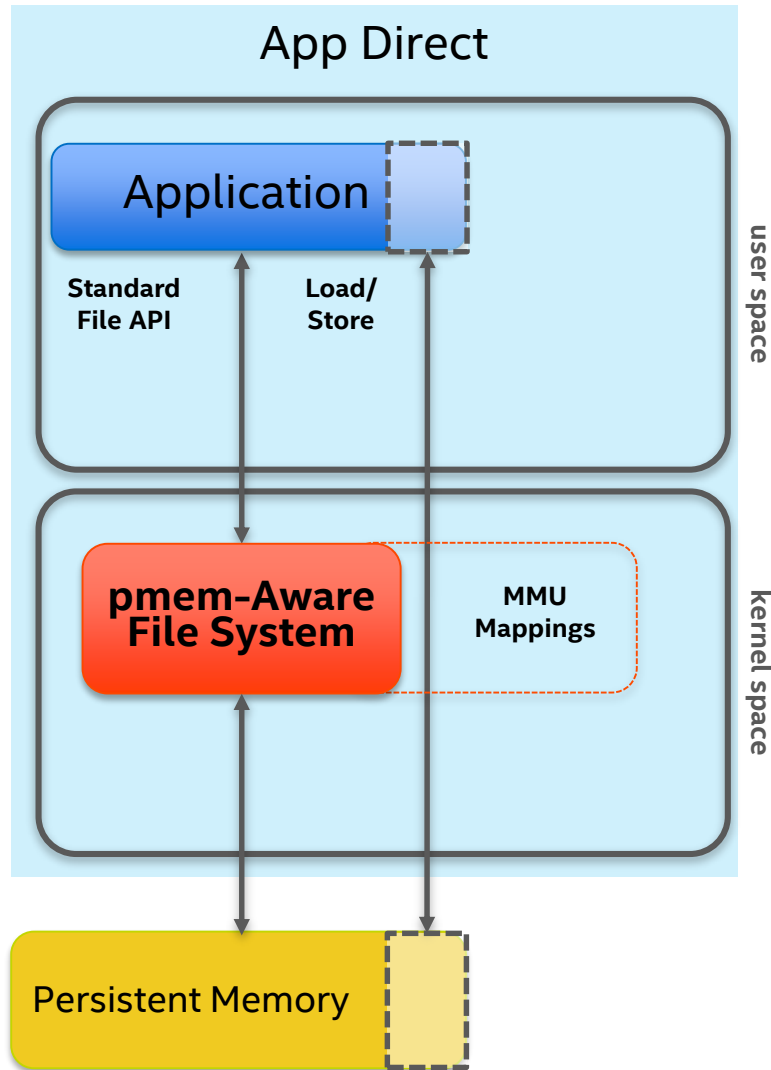
Storage Over App Direct

- Operates in blocks like SSD/HDD
 - Traditional read/write instructions
 - Works with existing file systems
 - Atomicity at block level
 - Block size configurable (4K, 512B)
- NVDIMM driver required
 - Support starting kernel 4.2
- Scalable capacity
- Higher endurance than enterprise class SSDs
- High performance block storage
 - Low latency, higher bandwidth, high IOPs

Linux kernel and driver changes: https://www.youtube.com/watch?v=owmN_lcMK2M



SNIA NVM PROGRAMMING MODEL

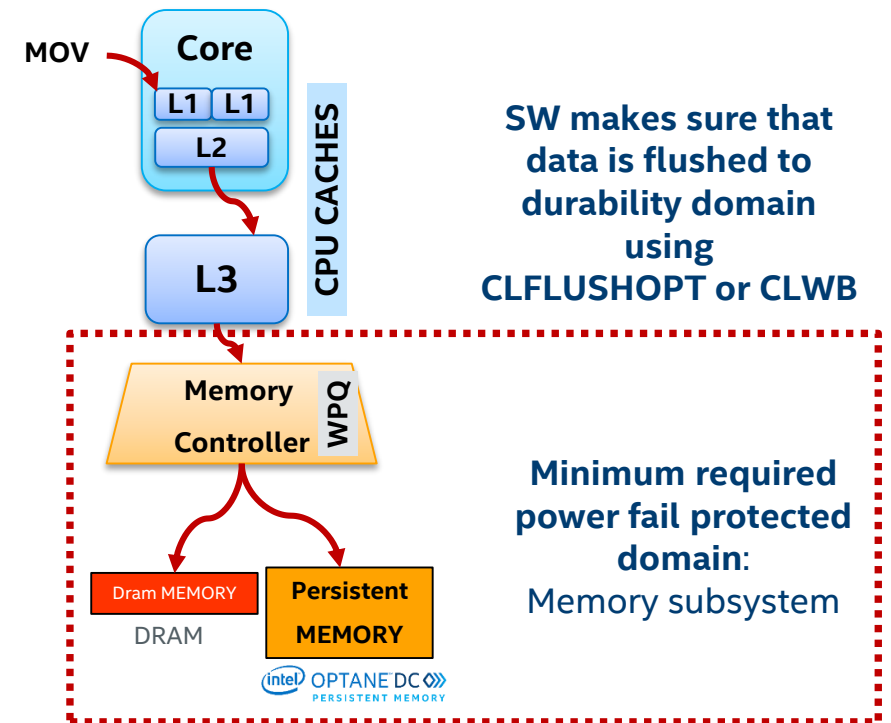


```
fd = open("/my/file", O_RDWR);
...
base = mmap(NULL, filesize,
            PROT_READ|PROT_WRITE,
            MAP_SHARED_VALIDATE|MAP_SYNC, fd, 0);
close(fd);
...
base[100] = 'X';
strcpy(base, "hello there");
msync(...);
...
```

PERSISTENT MEMORY USAGE MODES

App Direct Mode details

- PMEM-aware software/application required
 - Adds a new tier between DRAM and block storage (SSD/HDD)
 - Industry open standard programming model and Intel PMDK
- In-place persistence
 - No paging, context switching, interrupts, nor kernel code executes
- Byte addressable like memory
 - Load/store access, no page caching
- Cache Coherent
- Ability to do DMA & RDMA

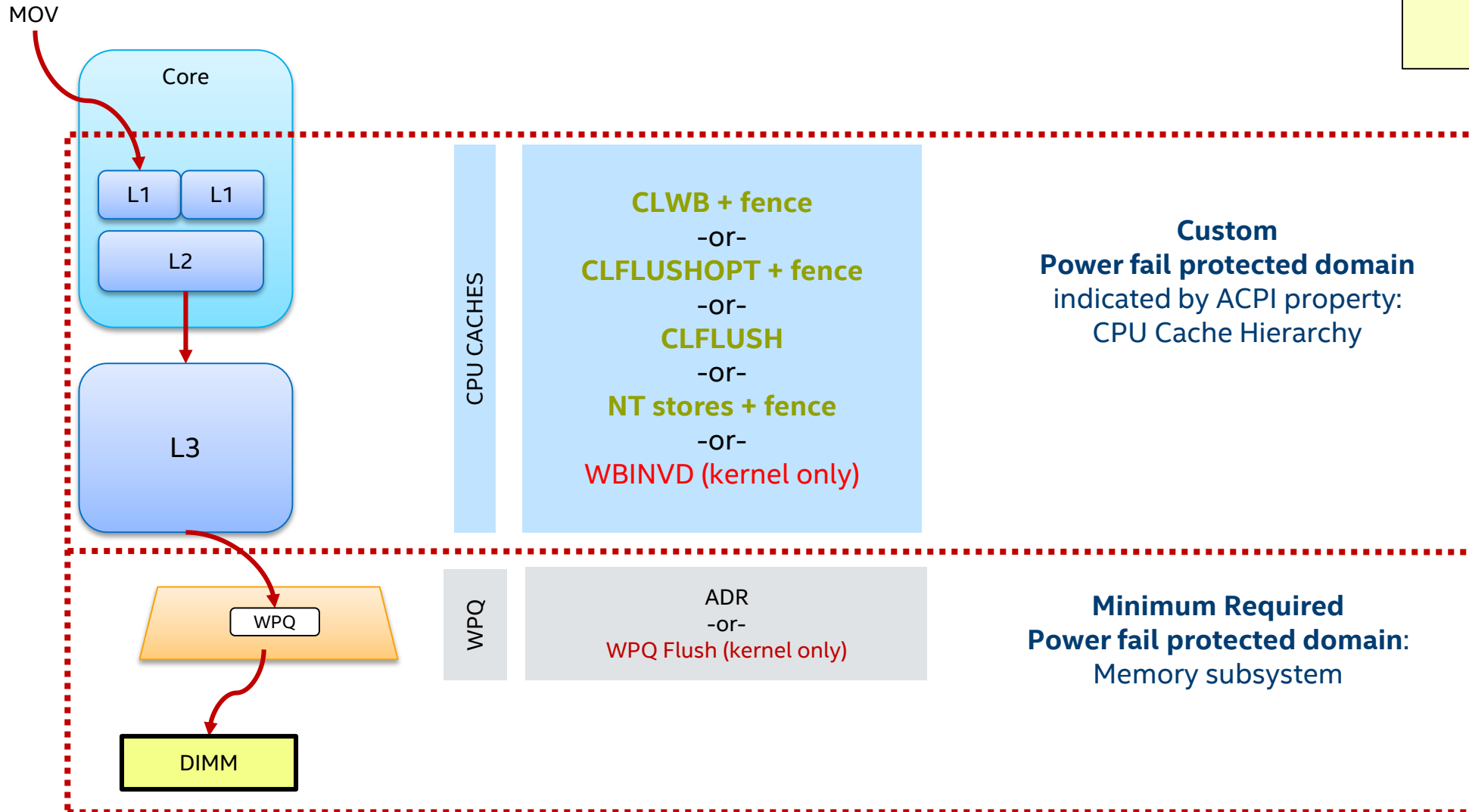


PERSISTENT MEMORY USAGE MODES

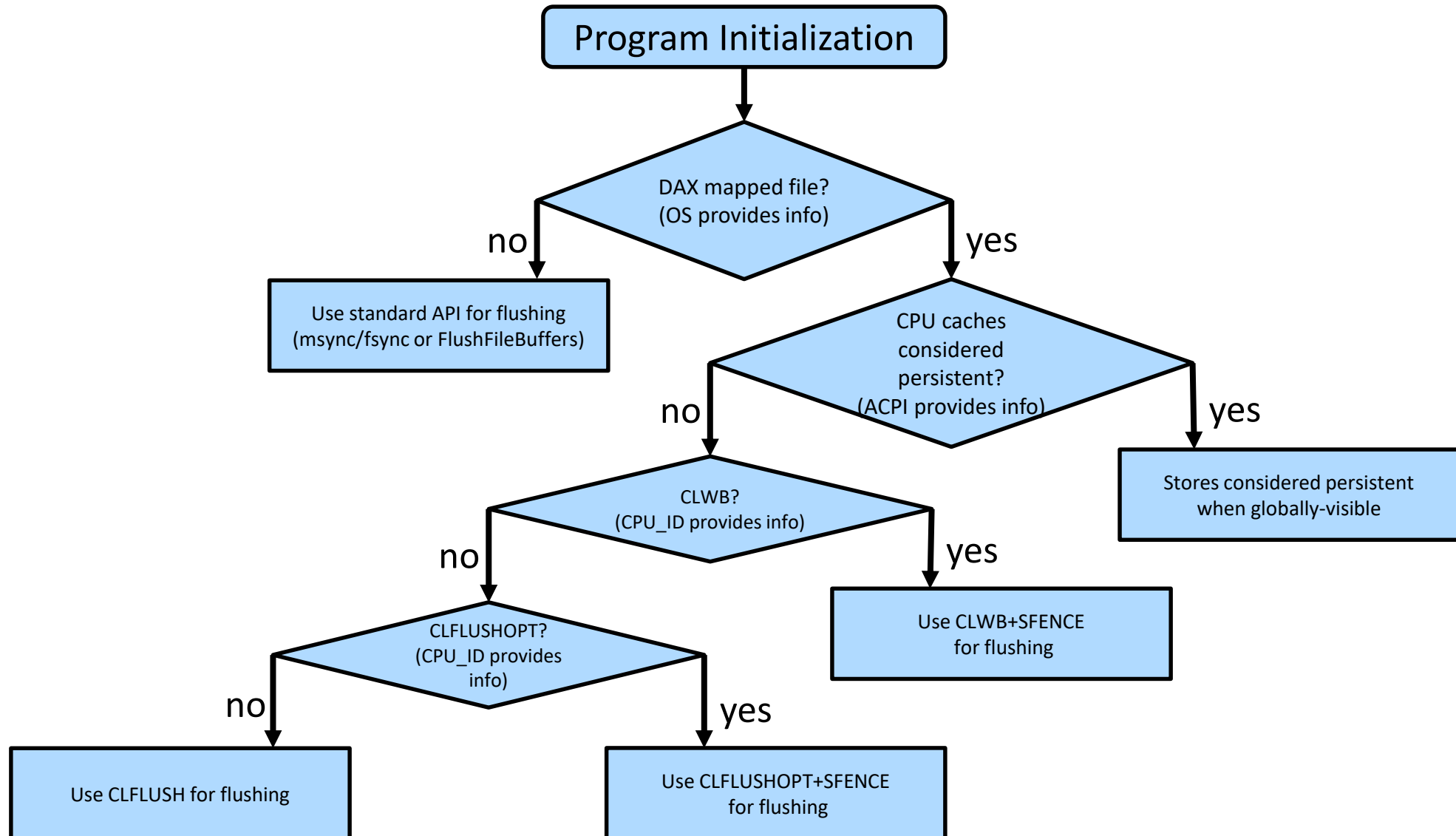
Summary

Volatile (use pmem for its capacity)		Persistent (leverage the fact pmem is persistent)	
Unmodified Apps	Modified Apps	Unmodified Apps	Modified Apps
Lowest impact Transparent for Apps	Low impact App decides on data placement	Lowest impact Apps use Storage API	Highest impact pmem-resident data structures
<i>Memory Mode</i>	<i>App Direct</i>	<i>App direct</i>	<i>App Direct</i>

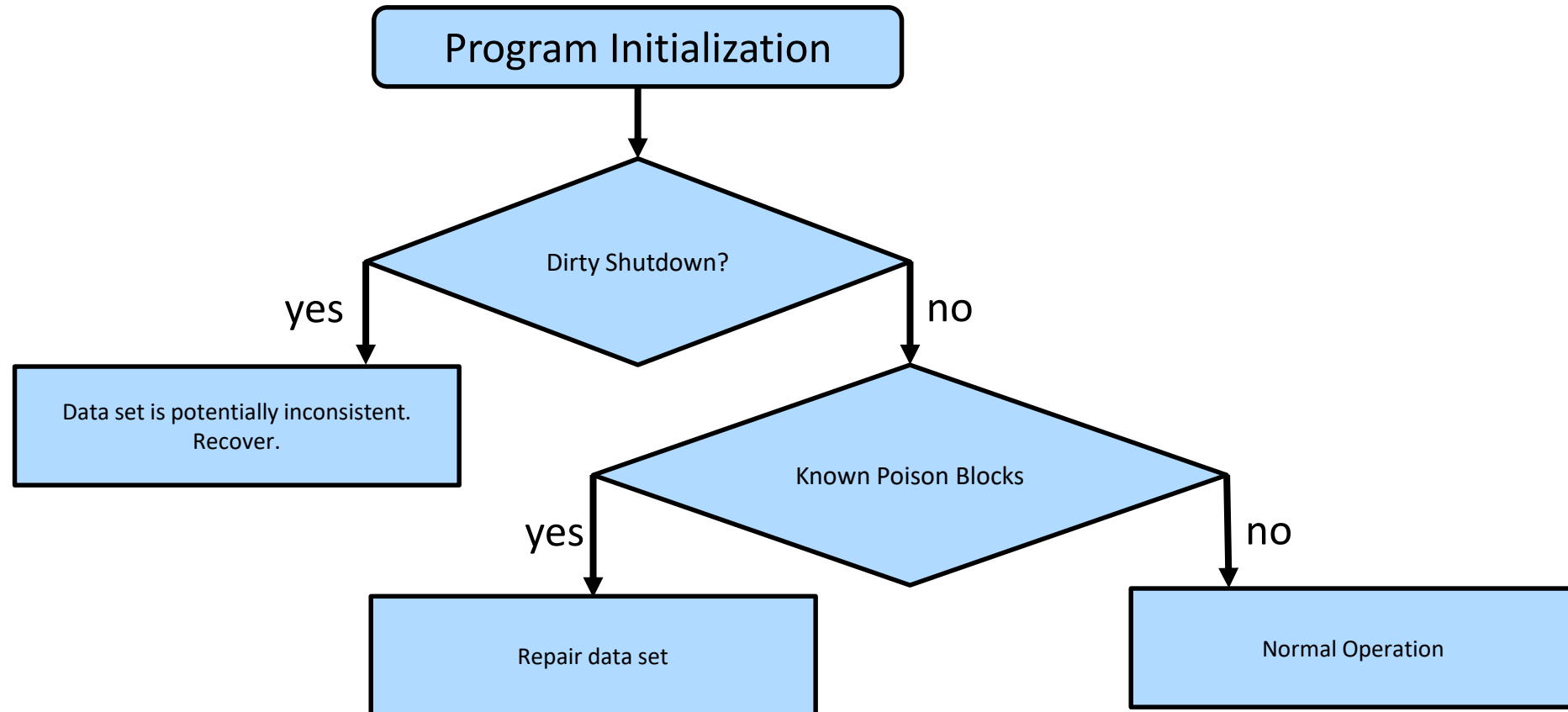
HOW THE HARDWARE WORKS



APPLICATION RESPONSIBILITIES: FLUSHING



APPLICATION RESPONSIBILITIES: RECOVERY



APPLICATION RESPONSIBILITIES: CONSISTENCY

```
open(...);  
  
mmap(...);  
  
strcpy(pmem, "Hello, World!");  
  
msync(...);
```

APPLICATION RESPONSIBILITIES: CONSISTENCY

```
open(...);  
mmap(...);  
strcpy(pmem, "Hello, World!");  
pmem_persist(pmem, 14);
```

← Crash

Result

1. "\0\0\0\0\0\0\0\0\0\0..."
2. "Hello, w\0\0\0\0\0\0\0..."
3. "\0\0\0\0\0\0\0\0\0orld!\0"
4. "Hello, \0\0\0\0\0\0\0\0"
5. "Hello, World!\0"

APPLICATION RESPONSIBILITIES: CONSISTENCY

```
open(...);  
mmap(...);  
strcpy(pmem, "Hello, World!");  
pmem_persist(pmem, 14);
```

Crash

`pmem_persist()` may be faster,
but is still **not** transactional

Result

1. "\0\0\0\0\0\0\0\0\0\0..."
2. "Hello, w\0\0\0\0\0\0..."
3. "\0\0\0\0\0\0\0\0world!\0"
4. "Hello, \0\0\0\0\0\0\0\0"
5. "Hello, World!\0"

VISIBILITY VERSUS POWER FAIL ATOMICITY

Feature	Atomicity
Atomic Store	8 byte power-fail atomicity Much larger visibility atomicity
TSX	Programmer must comprehend XABORT, cache flush can abort
LOCK CMPXCHG	Non-blocking algorithms depend on CAS, but CAS doesn't include flush to persistence

Software must implement all atomicity beyond 8 bytes for pmem
Transactions are fully up to software

PMEM reference counter – BAD example

```
struct my_object {
    uint64_t refcount;
    type some_resource;
};

static void object_ref(struct my_object *object) { /* No decision based on this value in this thread...
    __sync_fetch_and_add(&object->refcount, 1); /* visible = 1 persistent = ? */
    persist(&object->refcount, sizeof(object->refcount)); /* visible = 1 persistent = 1 */
}

static void object_deref(struct my_object *object) { /* Decision is made based on visible but not persistent value
    if (__sync_sub_and_fetch(&object->refcount, 1) == 0) { /* visible = 0 persistent = ? */
        delete_some_resource(object->some_resource); /* visible = 0 persistent = ? */
    }
    persist(&object->refcount, sizeof(object->refcount)); /* visible = 0 persistent = 0 */
}
```

PMEM reference counter – GOOD example

```
struct my_object {
    uint64_t refcount;
    type some_resource;
};

static void object_ref(struct my_object *object) { /* refcount visible = 0 persistent = 0 */
    __sync_fetch_and_add(&object->refcount, 1); /* visible = 1 persistent = ? */
    persist(&object->refcount, sizeof(object->refcount)); /* visible = 1 persistent = 1 */
}

static void object_deref(struct my_object *object) { /* visible = 1 persistent = 1 */
    if (__sync_sub_and_fetch(&object->refcount, 1) == 0) { /* visible = 0 persistent = ? */
        persist(&object->refcount, sizeof(object->refcount)); /* visible = 0 persistent = 0 */
        delete_some_resource(object->some_resource); /* visible = 0 persistent = 0 */
    } else {
        persist(&object->refcount, sizeof(object->refcount));
    }
}
```

No decision based on this value in this thread...

Decision is based on a known persistent value

Atomic variables need to be read and flushed before making any decisions/calculations with them to ensure that the action is taken on a value that is known to have been persistent at some point.

