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Persistent memory: new tier or storage replacement?

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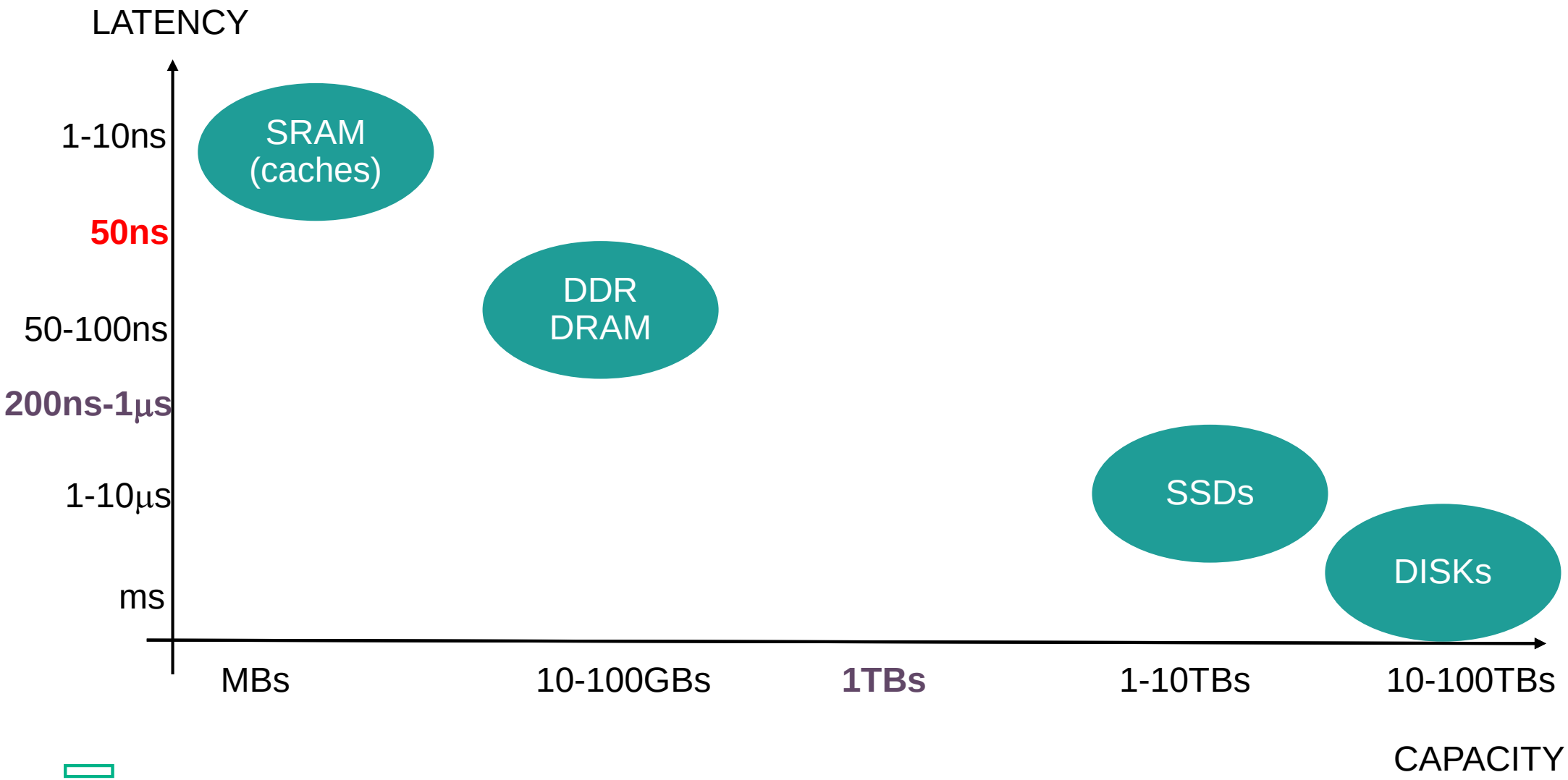
Labs

Outline

- Persistent memory blurs boundaries between memory and storage
- Memory-Driven Computing (MDC) – context for our work with persistent memory
- Memory-Driven Computing software
- Challenges for persistent memory as storage
- Summary

Memory + storage hierarchy technologies



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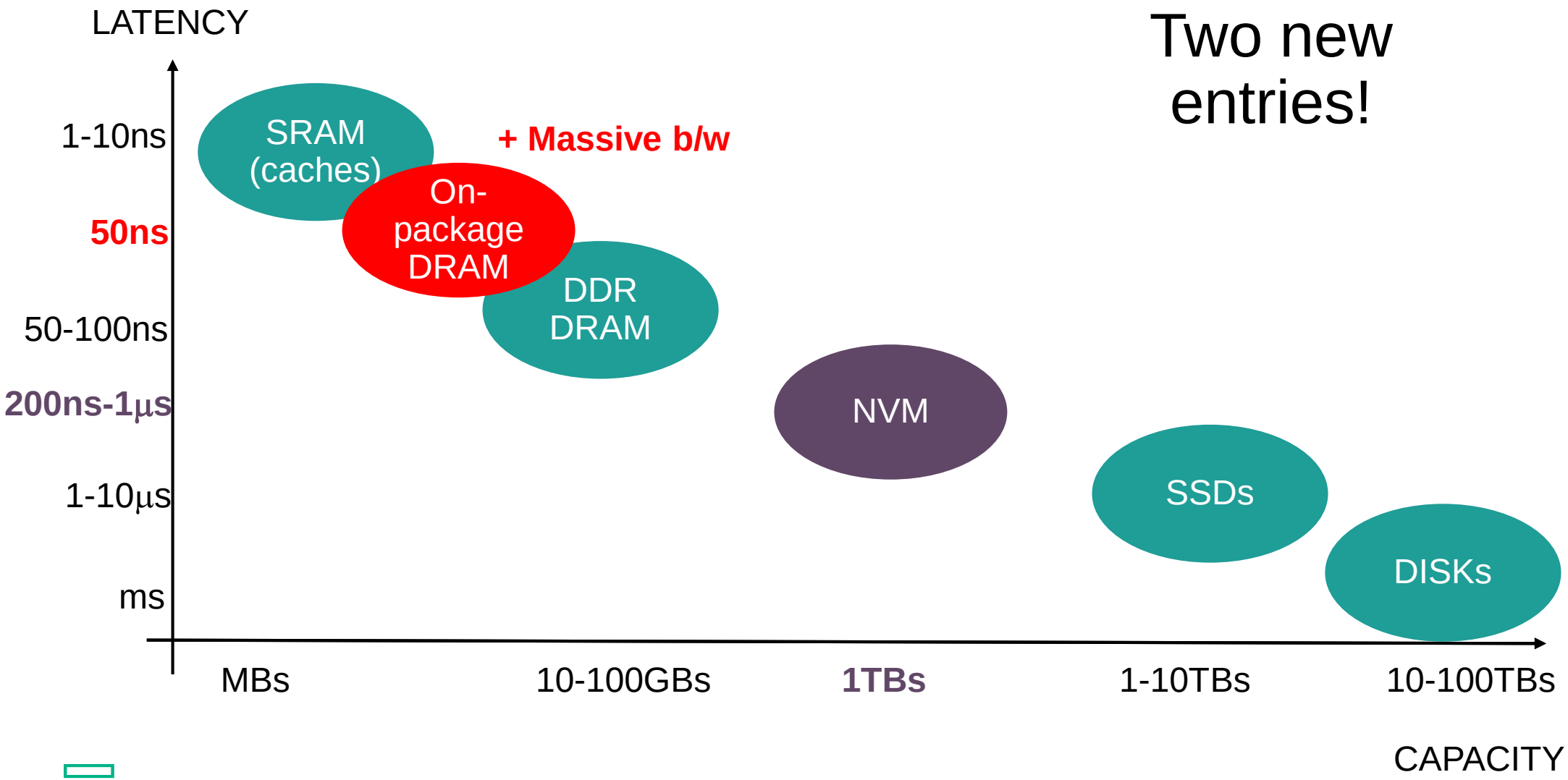
Memory + storage hierarchy technologies



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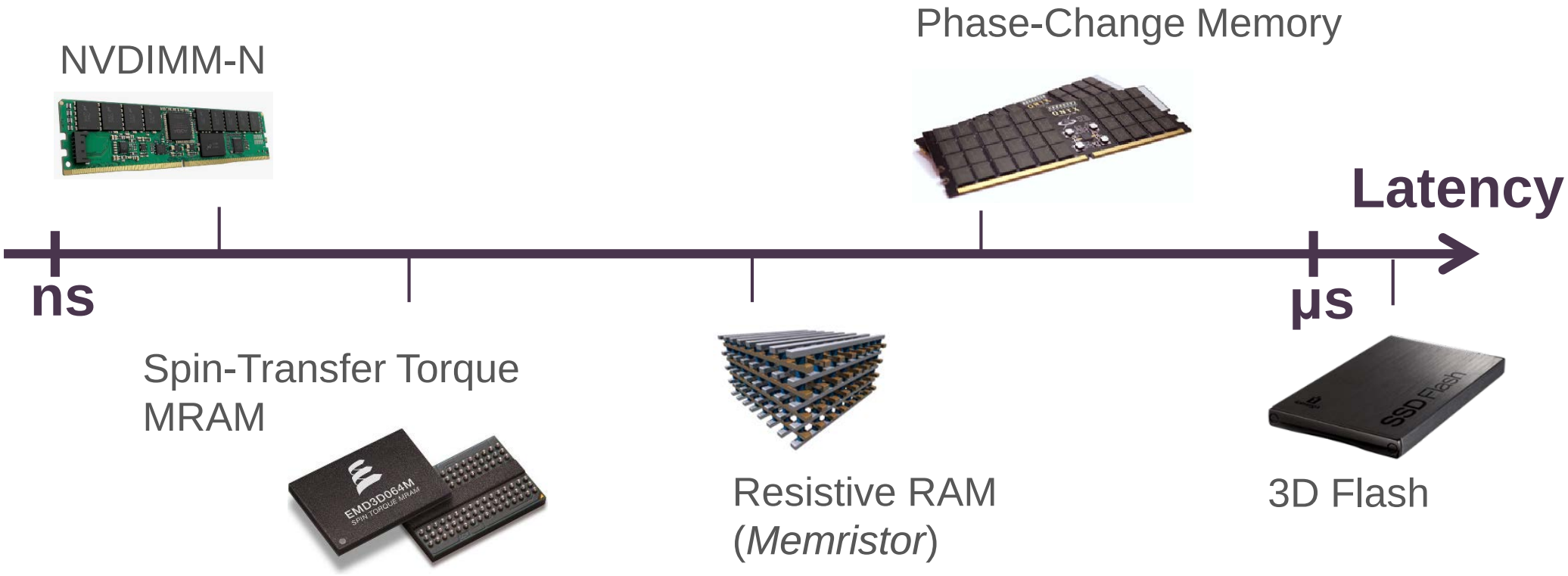
Non-Volatile Memory (NVM)



– Persistently stores data
– Access latencies comparable to DRAM
– Byte addressable (load/store) rather than block addressable (read/write)
– Some NVM technologies more energy efficient and denser than DRAM

Haris Volos, et al. "Aerie: Flexible File-System Interfaces to Storage-Class Memory," *Proc. EuroSys 2014*.

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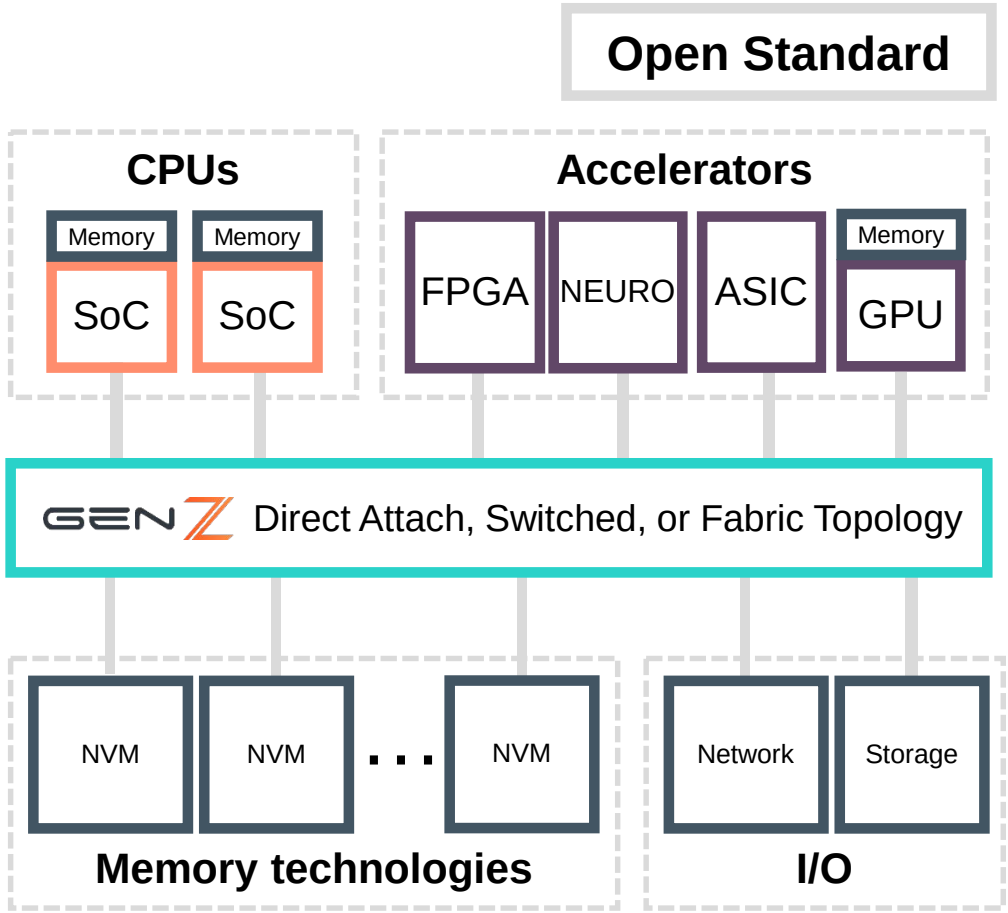
Gen-Z: open systems interconnect standard

http://www.genzconsortium.org

- Open standard for memory-semantic interconnect
- Members: 30+ companies covering SoC, memory, I/O, networking, mechanical, system software, etc.
- Motivation
  - Emergence of low-latency storage class memory
  - Demand for large capacity, rack-scale resource pools and multi-node architectures
- Memory semantics
  - All communication as memory operations (load/store, put/get, atomics)
- High performance
  - Tens to hundreds GB/s bandwidth
  - Sub-microsecond load-to-use memory latency
- *Draft spec available for public download*



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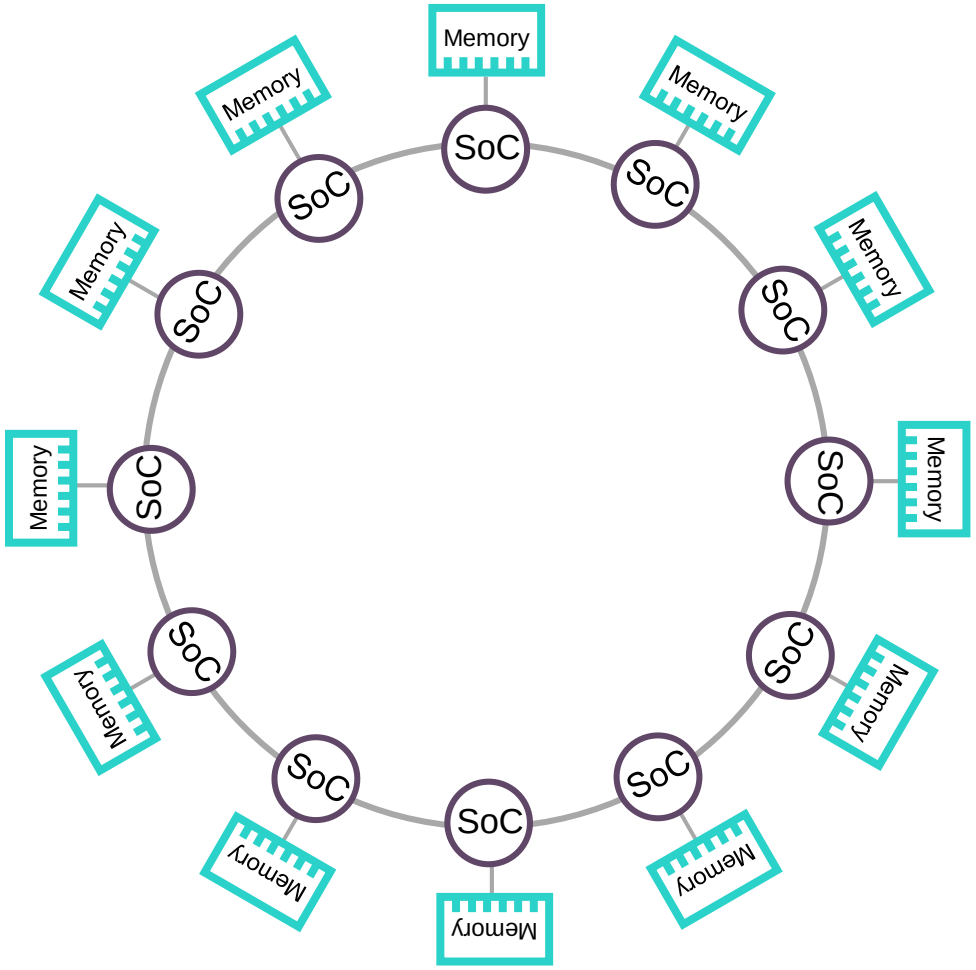
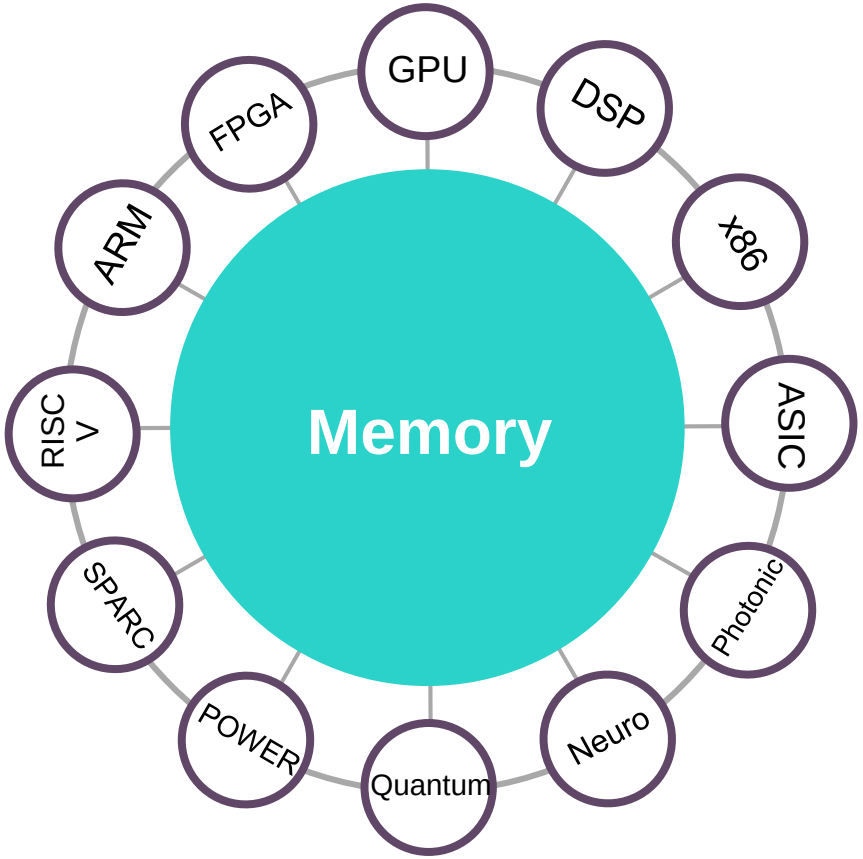
Today's architecture

From processor-centric computing



Future architecture

Memory-Driven Computing



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Core Memory-Driven Computing components

Fast, persistent memory

Fast memory fabric

Task-specific processing

New and Adapted software

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HPE introduces the world's largest single-memory computer

The prototype contains 160 terabytes of fabric-attached memory

- 160 TB of shared memory spread across 40 physical nodes, interconnected using a high-performance fabric protocol
- An optimized Linux-based operating system running on ThunderX2, Cavium's flagship second generation dual socket capable ARMv8-A workload optimized System on a Chip
- Photonics/Optical communication links, including the new X1 photonics module, are online and operational
- Software programming tools designed to take advantage of abundant of persistent memory

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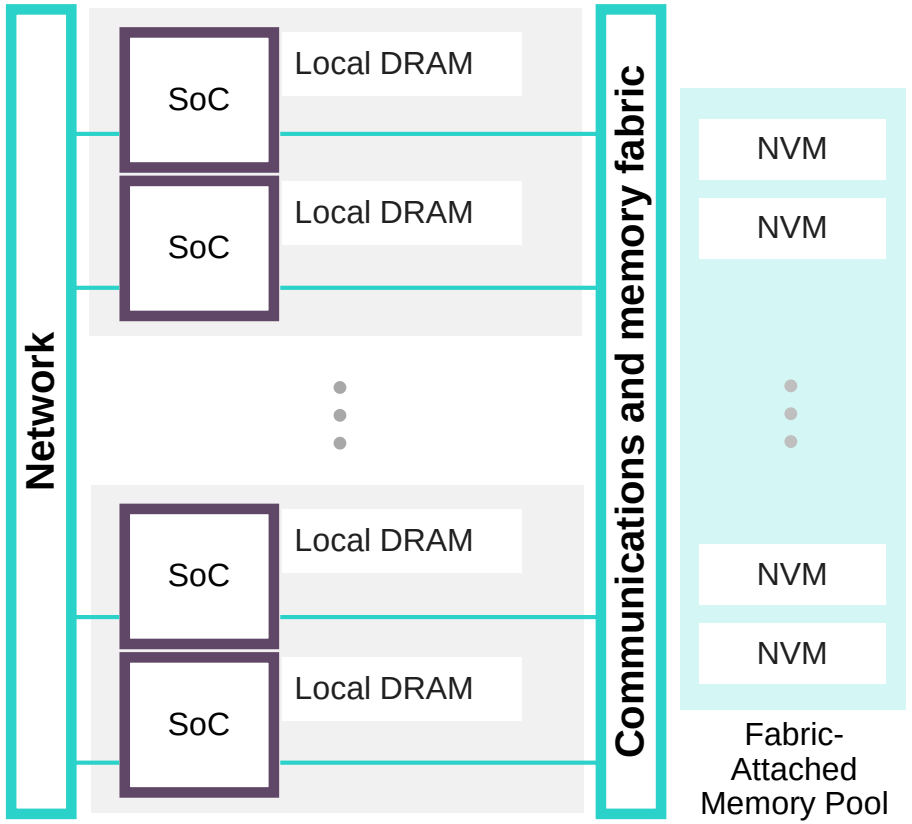
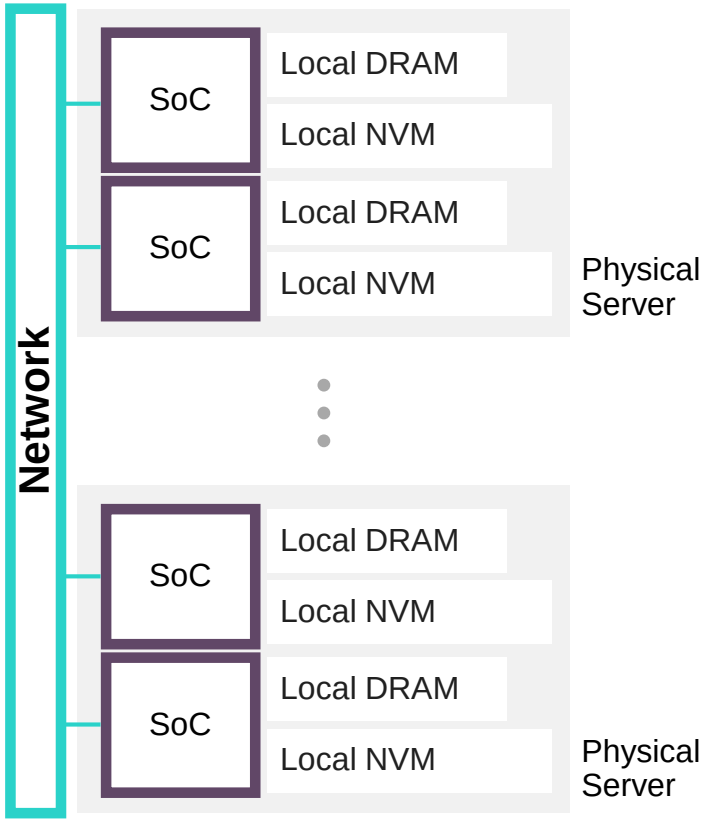
Putting it all together: Memory-Driven Computing

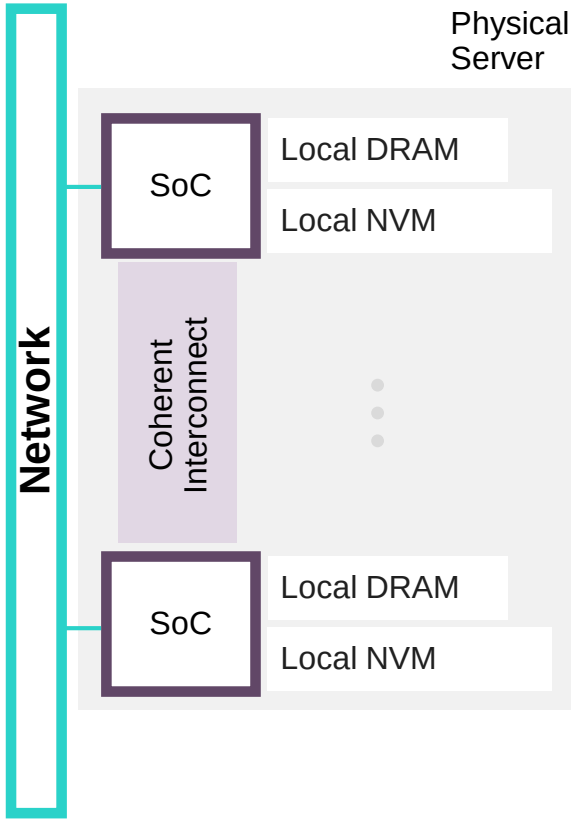


- **Converging memory and storage**
  - Byte-addressable NVM replaces hard drives and SSDs
- **Resource disaggregation leads to high capacity shared memory pool**
  - Fabric-attached memory pool is accessible by all compute resources
  - Low diameter networks provide near-uniform low latency
- **Local volatile memory provides lower latency, high performance tier**
- **Distributed heterogeneous compute resources**
- **Software**
  - Memory-speed persistence
  - Direct, unmediated access to all fabric-attached NVM across the memory fabric
  - Non-coherent accesses between compute nodes

Memory-Driven Computing in context



Shared nothing



Shared everything

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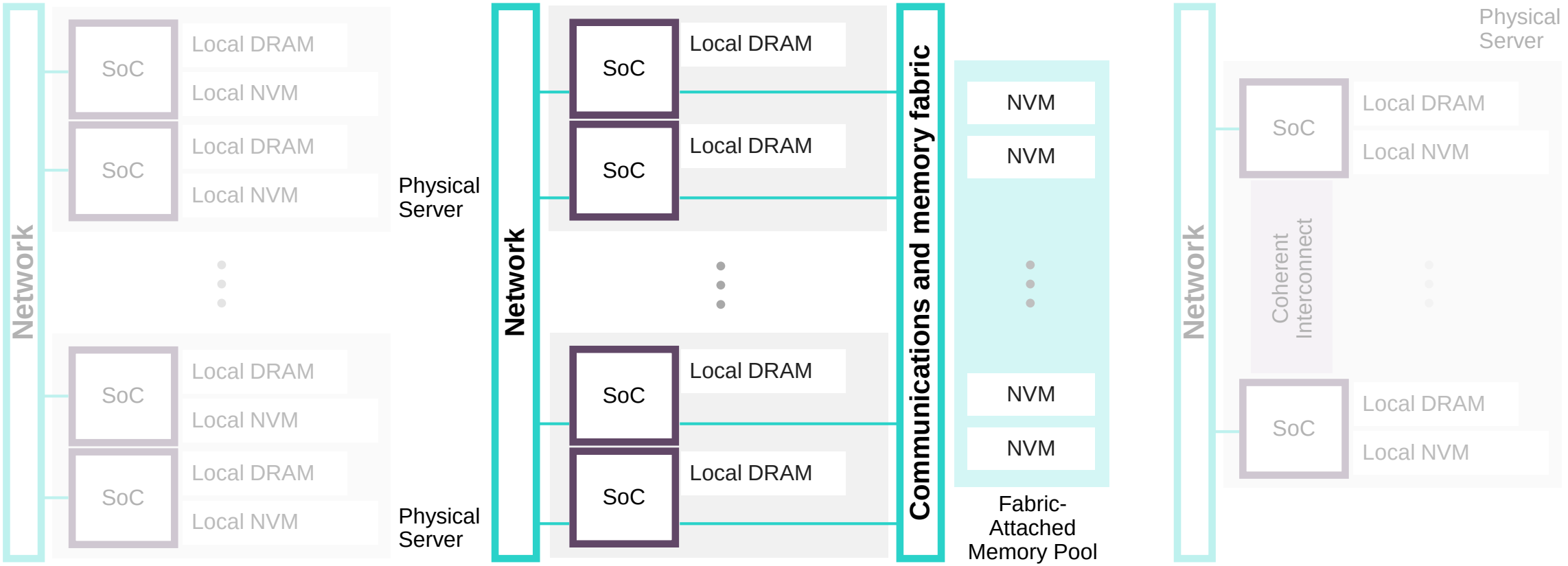
Memory-Driven Computing in context



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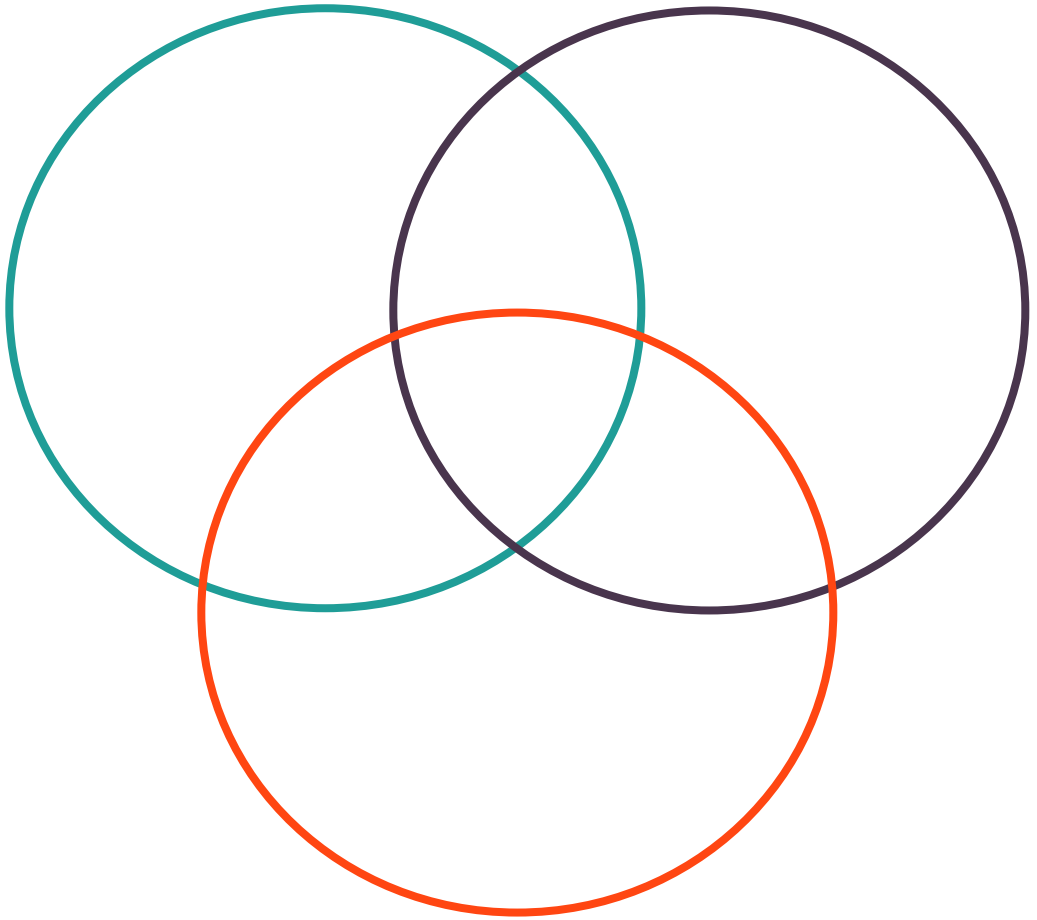
Questions driving work on MDC software

How do I ...

- use persistent memory?
- take full advantage of byte-addressable persistent memory?
- share data safely in a large, globally-addressable pool of memory?
- ensure data consistency in the face of failures and errors?
- scale effectively to use our large-memory, many-core systems?

Memory-Driven Computing delivered with systems software

Memory is large



Memory is shared non-coherently over fabric

Memory is persistent

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Memory-Driven Computing delivered with systems software

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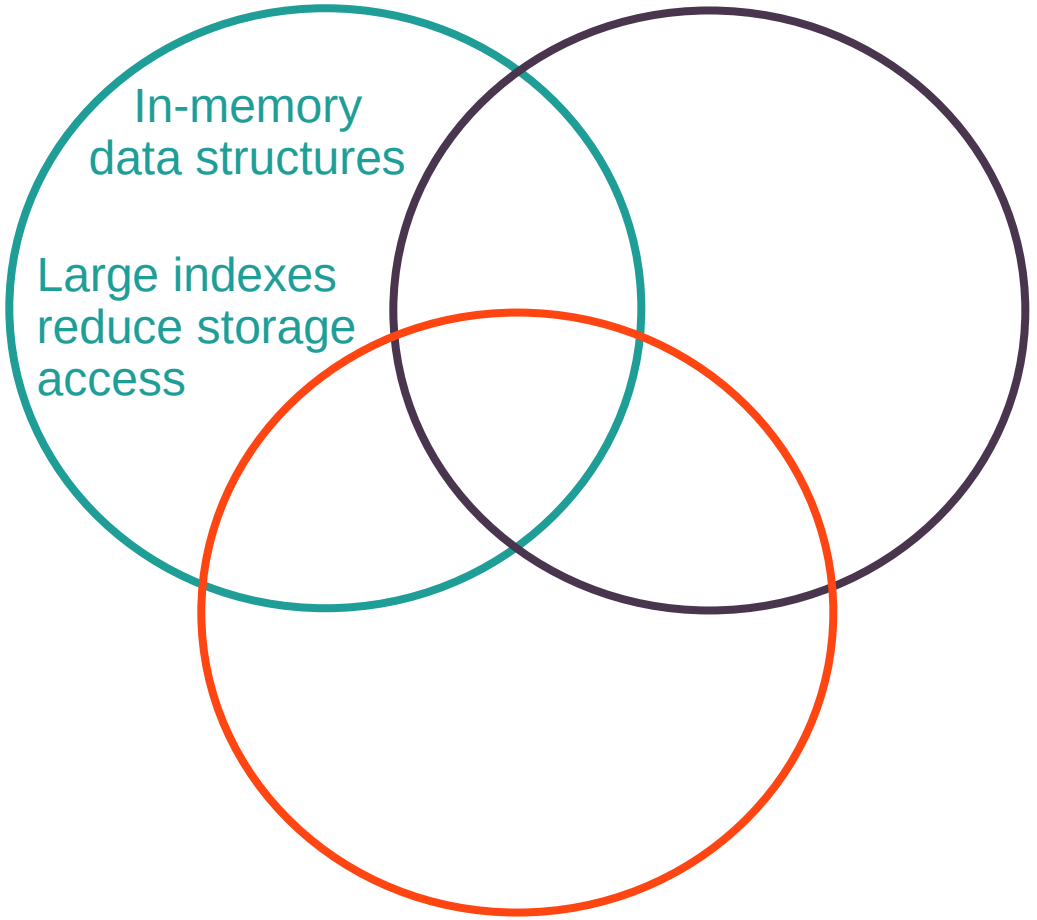

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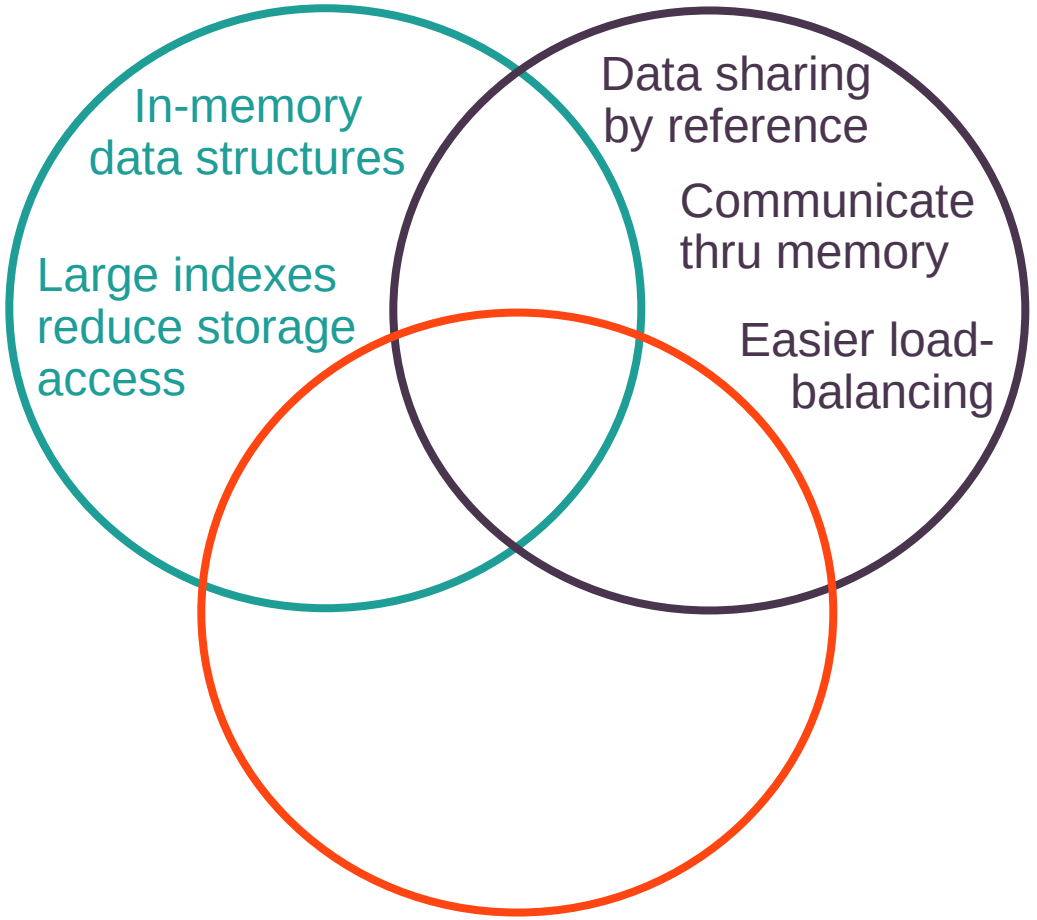

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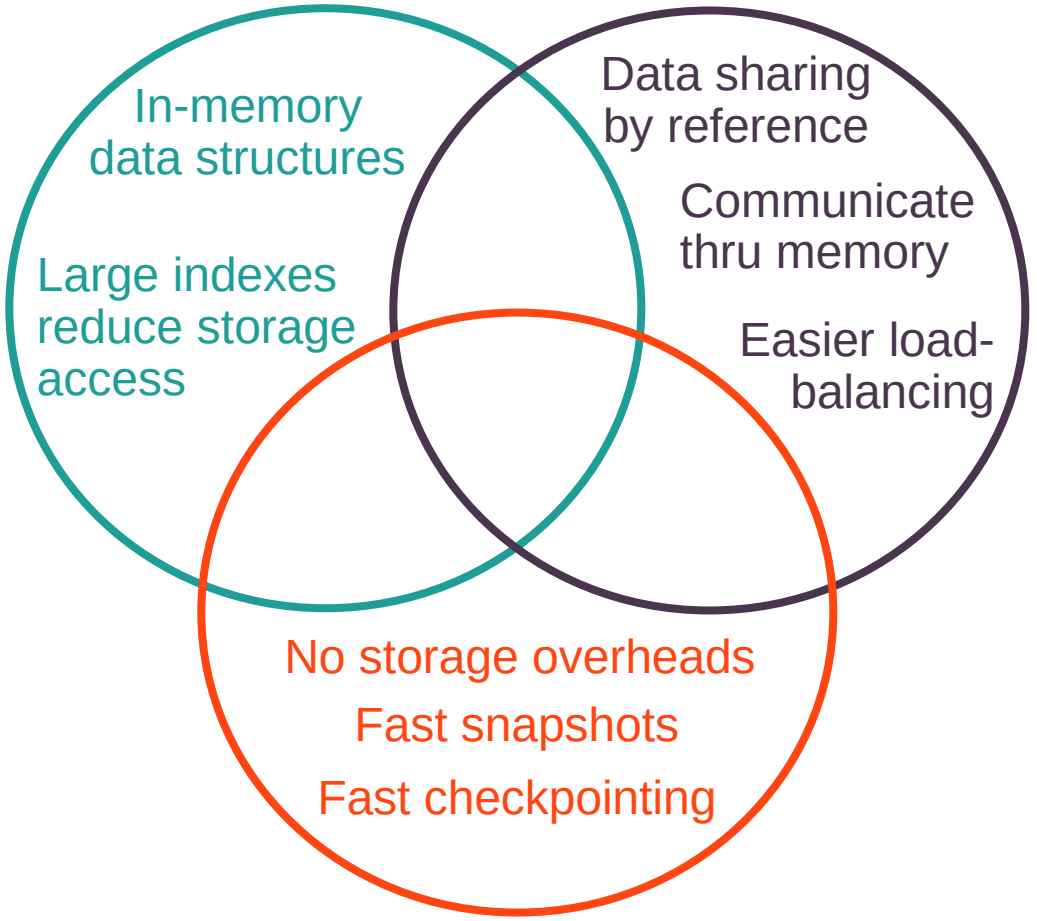

Memory is persistent

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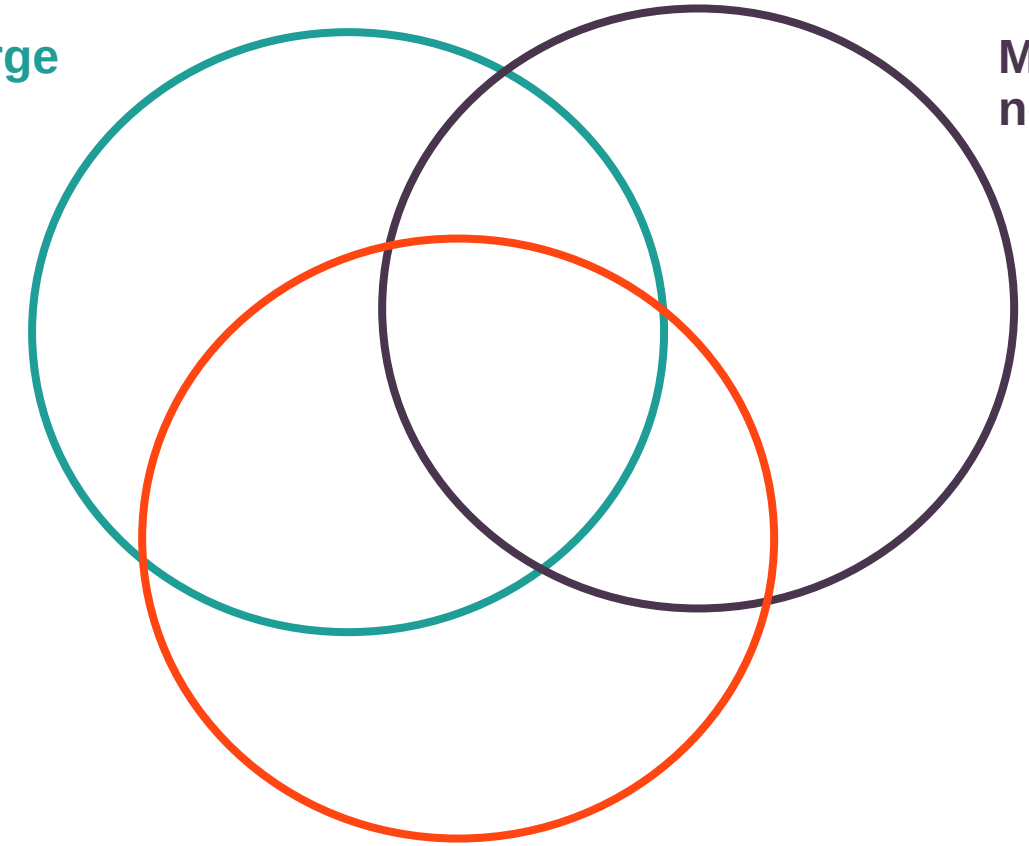
Memory-Driven Computing Developer Toolkit



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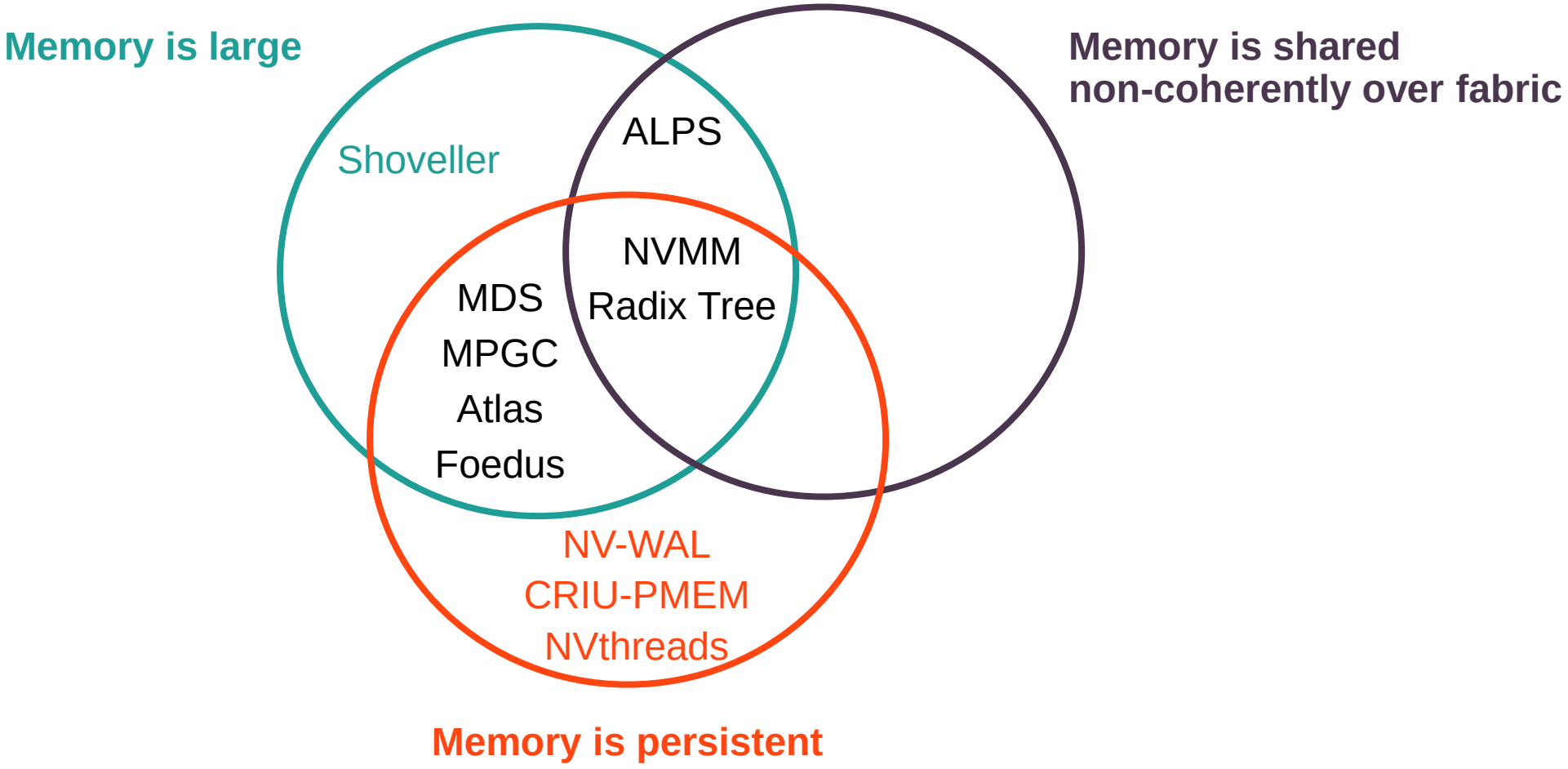
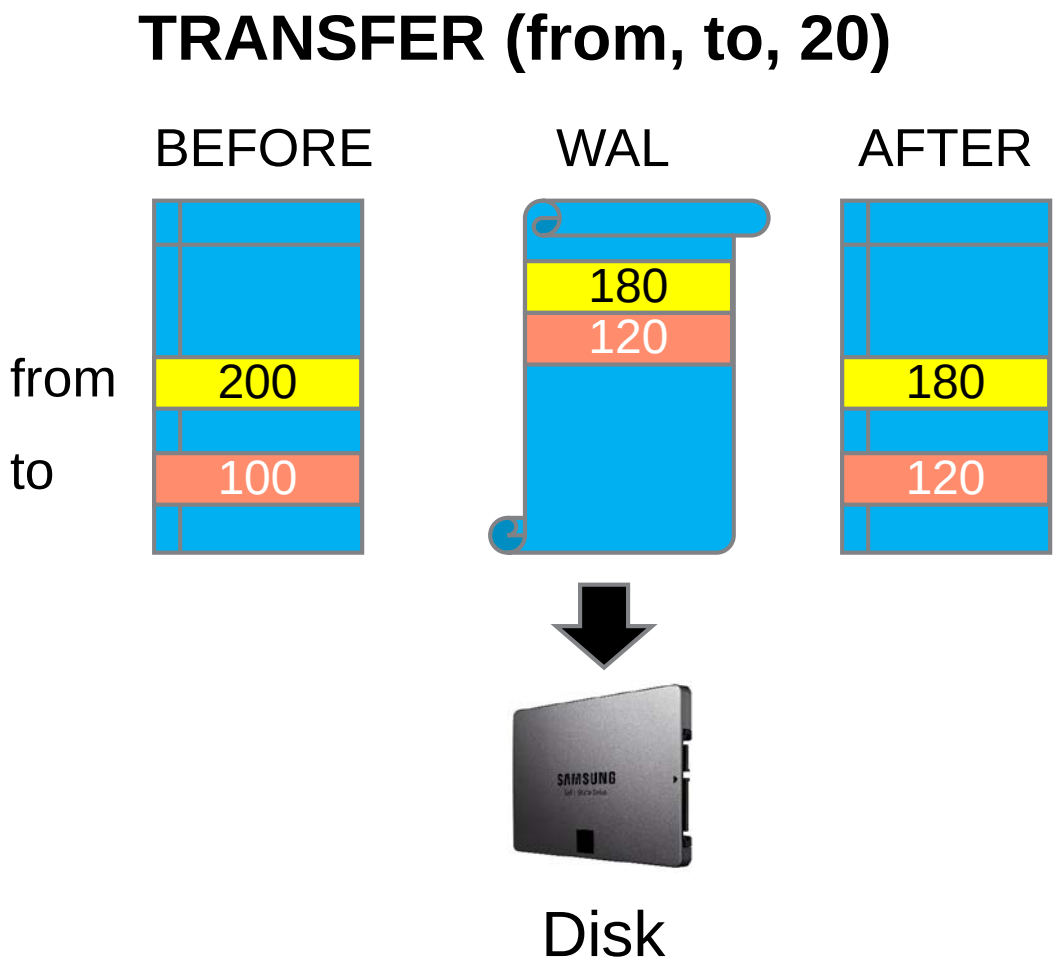


Libnvwal: Write-Ahead Logging Library

– Key mechanism for atomicity and durability
  – Atomicity: Record all modifications in WAL, and
  – Durability: Persist WAL before applying

```
TRANSFER (from, to, amount)
  transaction {
    from = from – amount
    to = to + amount
  }
```

– Persistence latency critical to transaction performance



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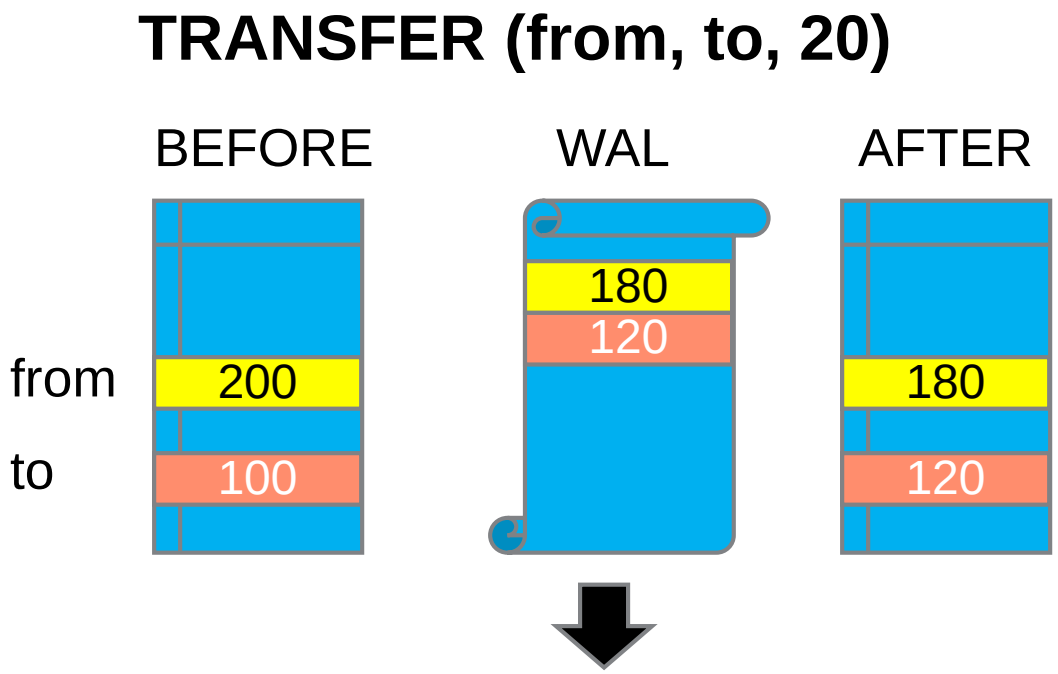
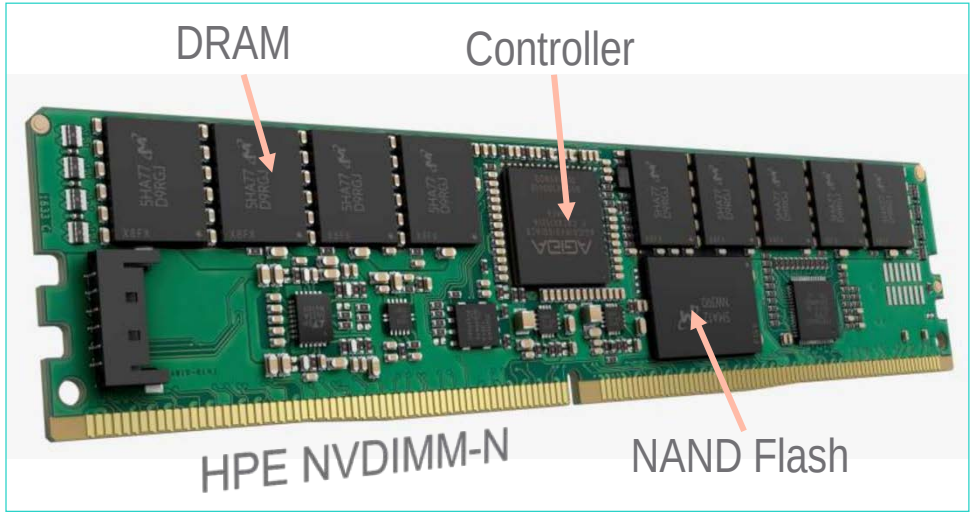
– Non-volatile memory DIMM (NVDIMM) enables low latency logging



Libnvwal: Hybrid NVDIMM/Disk Write-Ahead Logging

– NVDIMM enables low latency persistence
  – DRAM: Best performance/lowest latency for fast data access
  – NAND Flash: Persistent store for the NVDIMM
– But limited capacity (8GB NVDIMM today) requires truncating log
  – Requires checkpointing database
  – Precludes archiving log for disaster recovery



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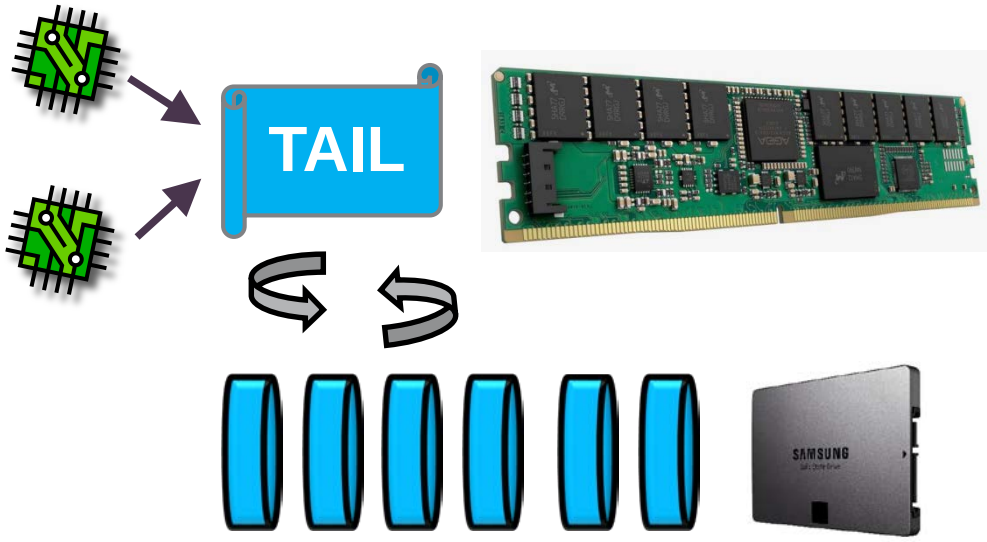
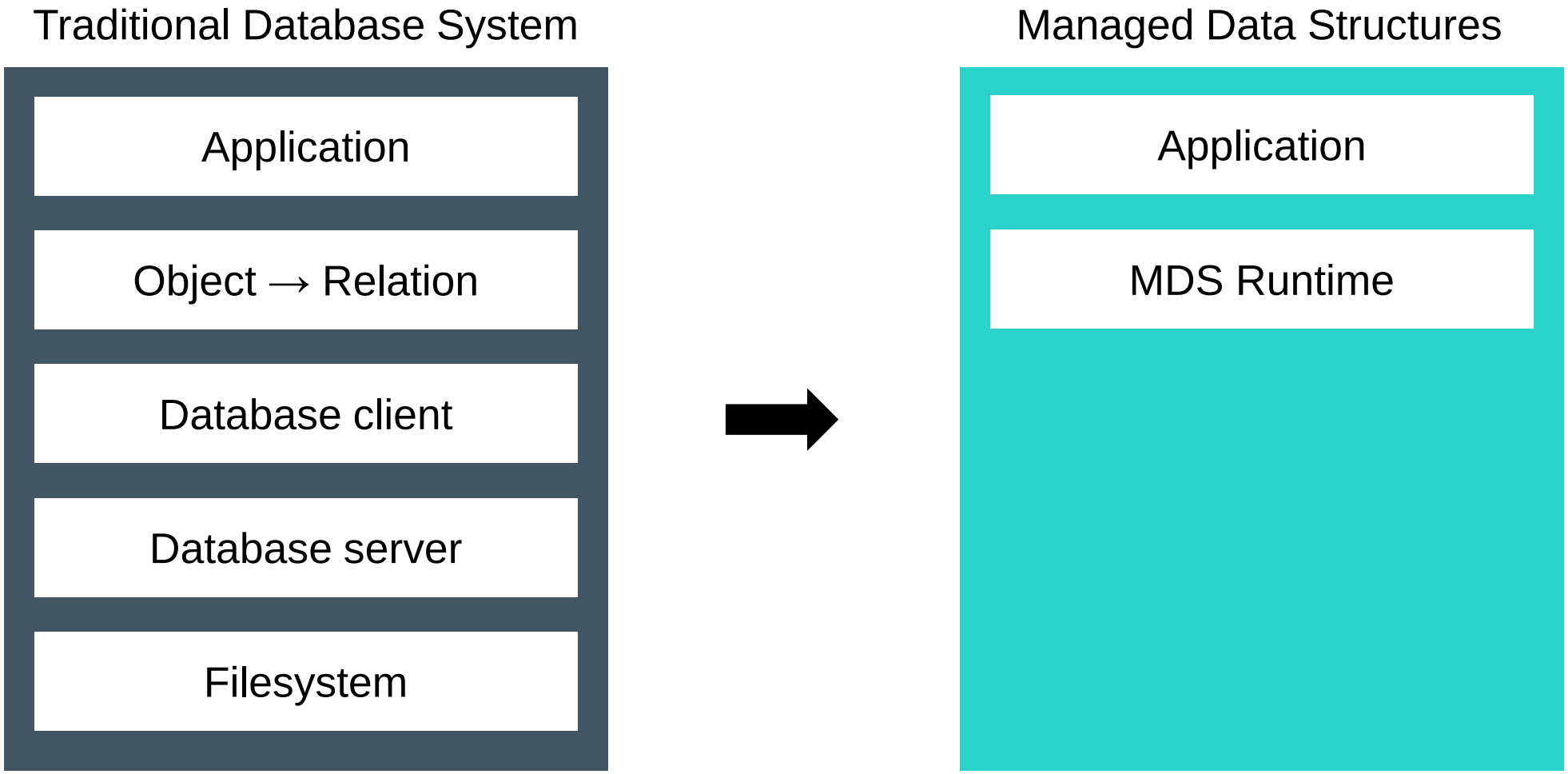
Libnvwal

– Stores log tail in NVDIMM for low-latency and de-stages log to disk for capacity
– Relieves application from implementing complex rotation logic
  – Non-trivial interaction between NVM buffers, file system, log metadata durability, and flushing threads
– Improves MySQL OLTP performance by up to 106% (sysbench)



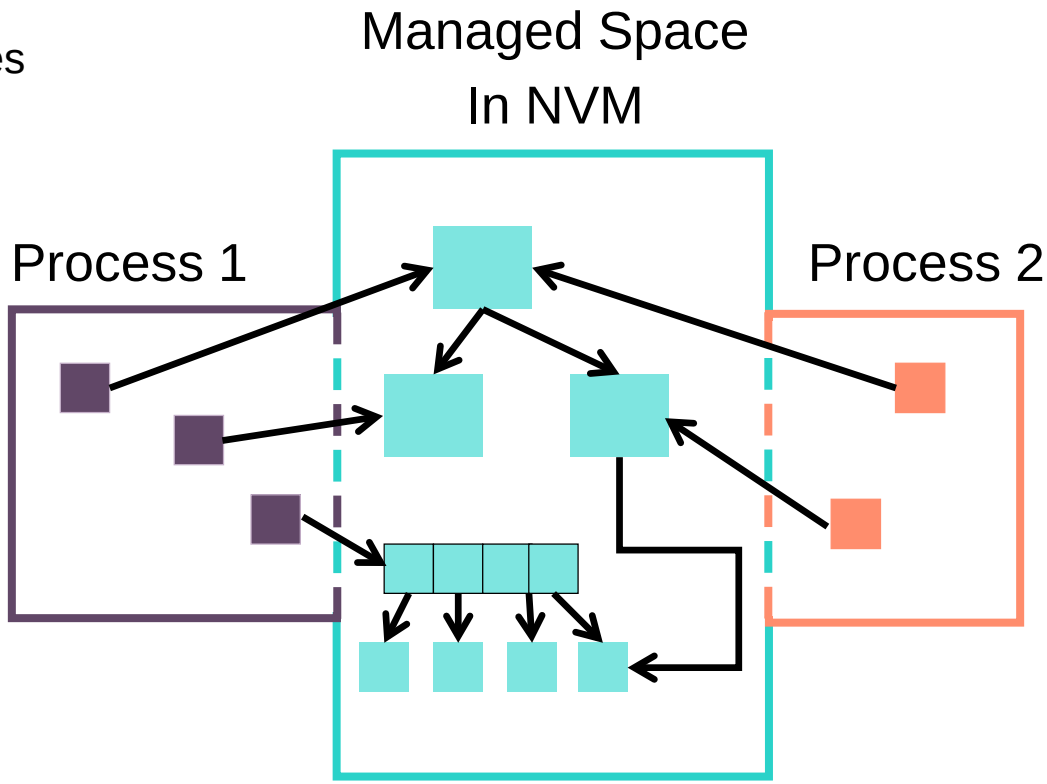
Fewer software layers



Managed Data Structures (MDS)

Simplify programming on persistent in-memory data

- Ease of Programming
  - Programmer manages only application-level data structures
    - Record, Array, Map, Set, Graph, List, Queue, …
    - MDS data structures are automatically persisted in NVM
  - APIs in multiple programming languages: Java, C++
    - Programmer access through references to data
    - Direct reads and writes
- Ease of Data Sharing
  - Just pass a reference
    - Each program treats the data as local to the program
  - High-level concurrency controls
    - Ensure consistent data in the face of data sharing by multiple threads/processes



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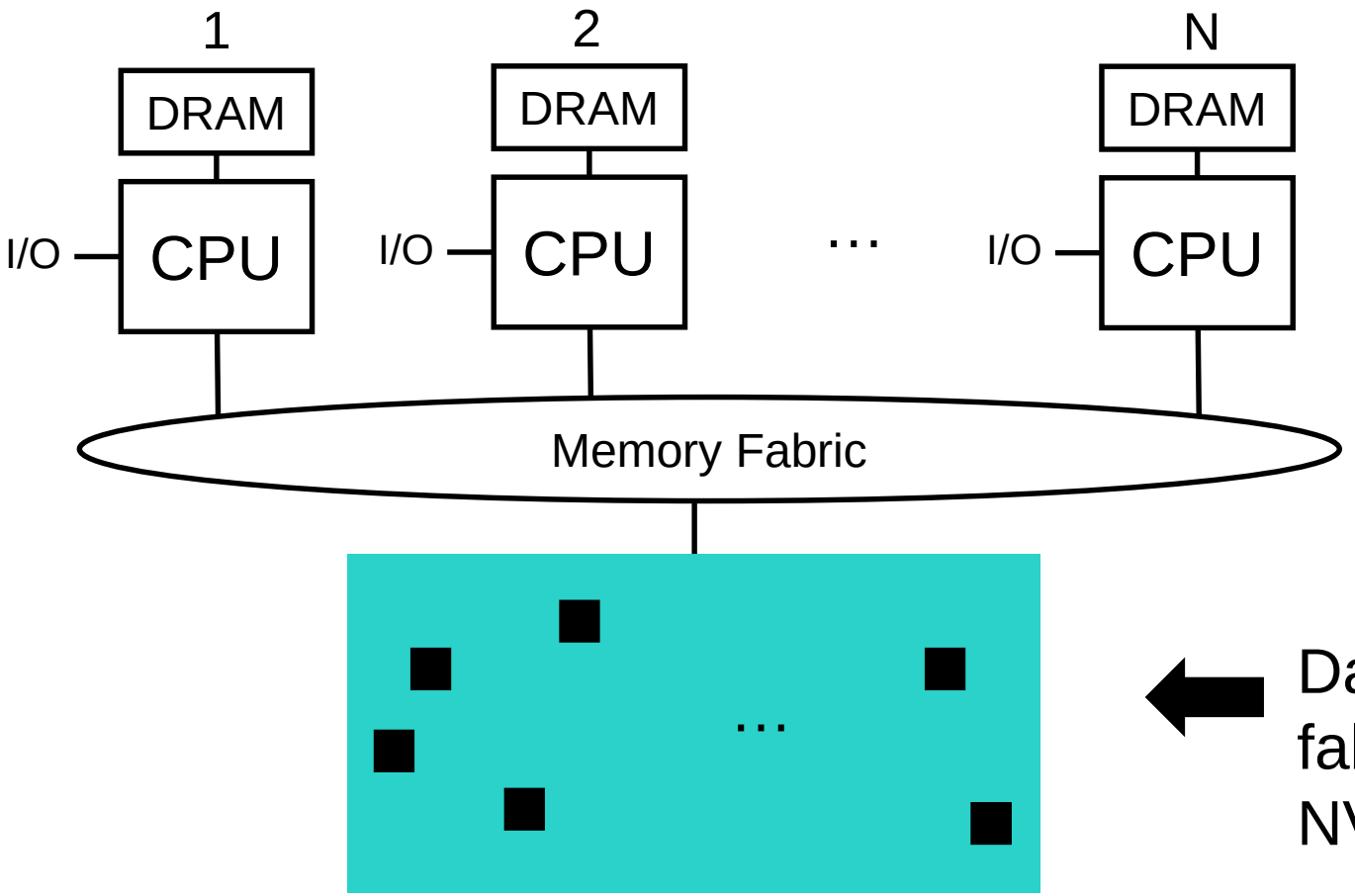
“Shared something” Key-Value Store (KVS)

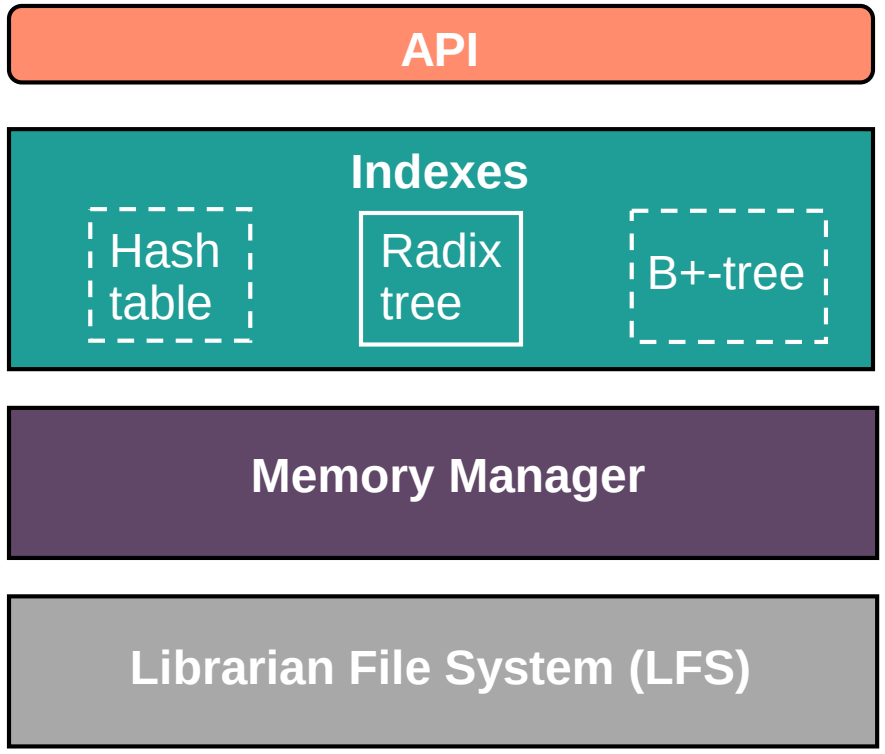
Leverage large pool of fabric-attached memory and fabric atomics

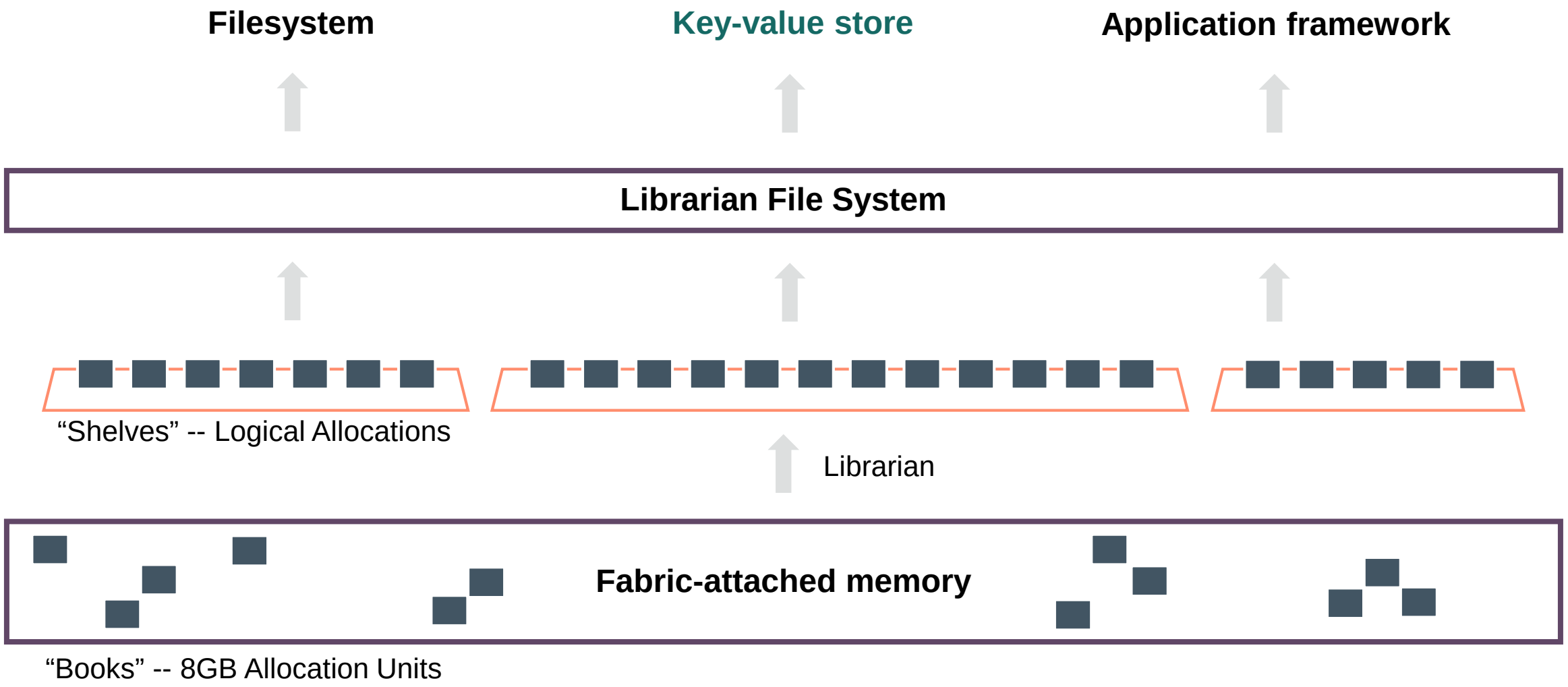


Data stored in fabric-attached NVM

High-level architecture for shared something KVS

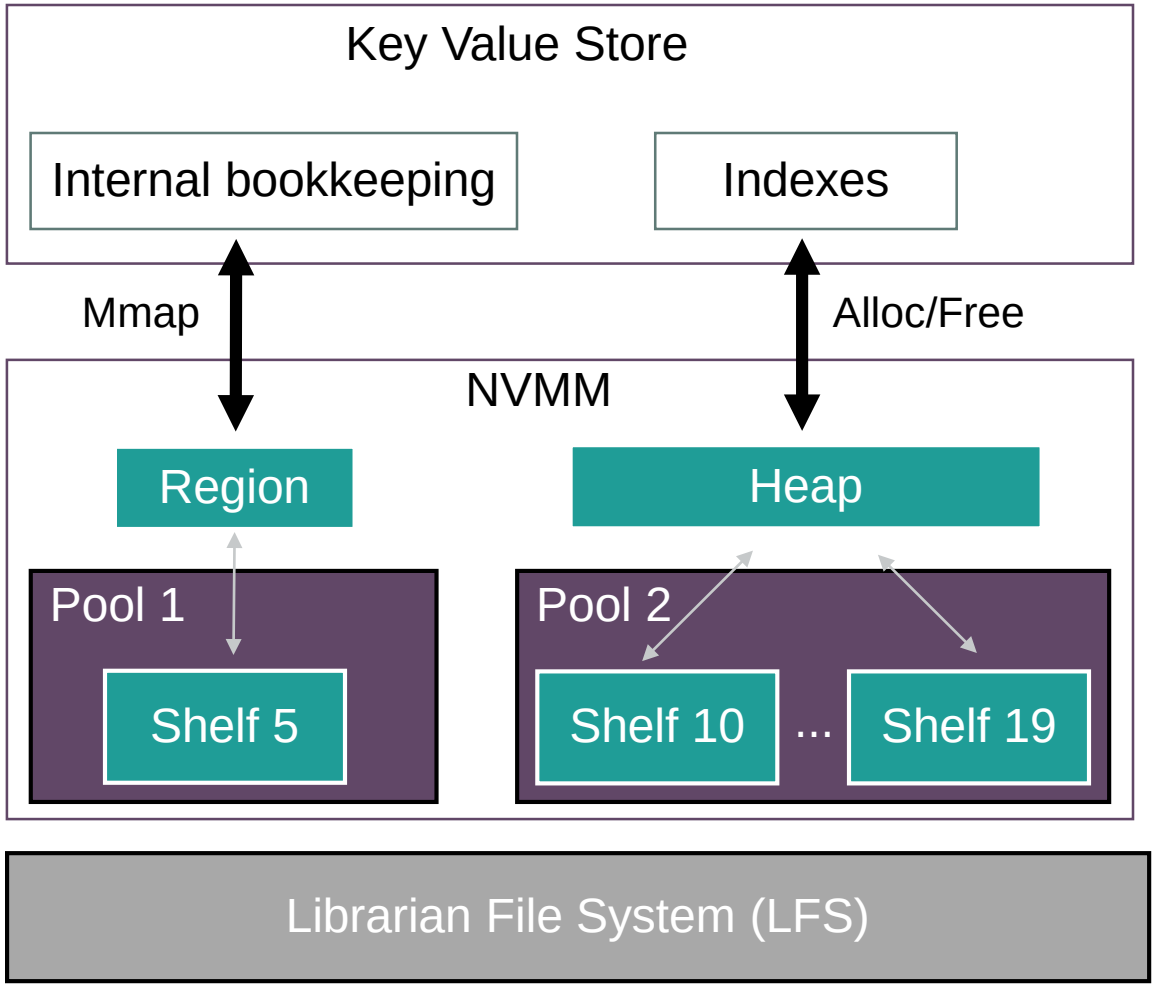
- What's different in fabric-attached memory (FAM)?
  - Memory semantic accesses (including atomics)
  - No hardware-based cache coherence between nodes
  - Separate fault domains between FAM and nodes
- Goal: multi-node, FAM-aware KVS
- How: exploit FAM and FAM atomics for
  - Concurrency control
  - Fault tolerance
  - Load balancing
- Open sourced components
  - Memory manager: MDC toolkit NVMM
  - Indexes: MDC toolkit radix tree





Non-volatile Memory Manager (NVMM)

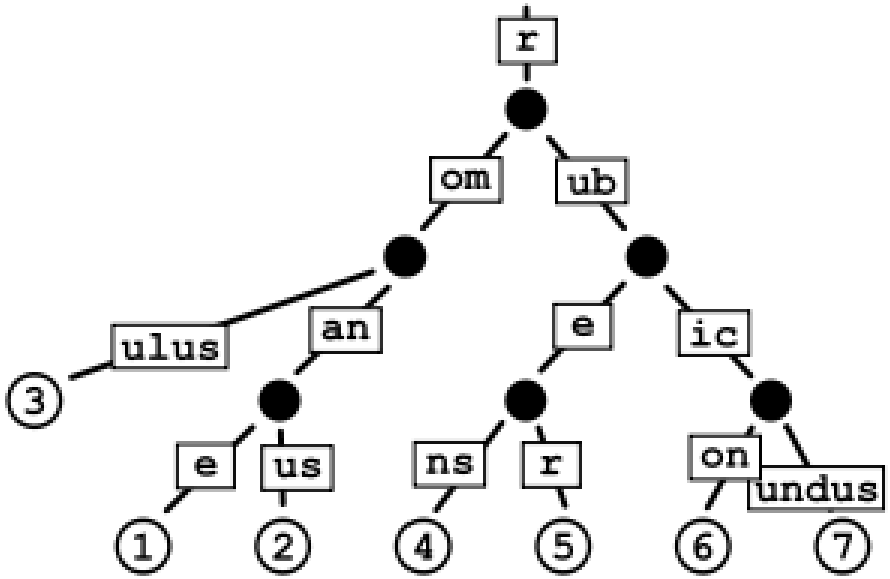
- Goals
  - Provide finer-grained memory allocation than LFS
  - Enable sharing across different processes and nodes
  - Tolerate failures of compute nodes and processes
- Manage shelves provided by LFS
  - Allocate, free, and name shelves (multiples of 8GBs)
  - Expose a global address space: {shelf ID, shelf offset}
- Memory access abstractions
  - *Region* APIs for direct memory-map access
  - *Heap* APIs for alloc/free style access
- Heap: allow any process from any node to allocate and free globally shared NVM transparently



Radix trees

- Also known as compact prefix tries
  - "Compress" common prefixes to improve space efficiency
- Maintain keys in sorted order
  - Support range (multi-key) lookups, unlike hash tables
- More amenable to FAM than B+-trees
  - Require fewer structural changes (e.g., node splits) as tree grows
  - Atomic operations used to insert or delete key and leave tree in consistent state

```
romane 1
romanus 2
romulus 3
rubens 4
ruber 5
rubicon 6
rubicundus 7
```



https://en.wikipedia.org/wiki/Radix_tree

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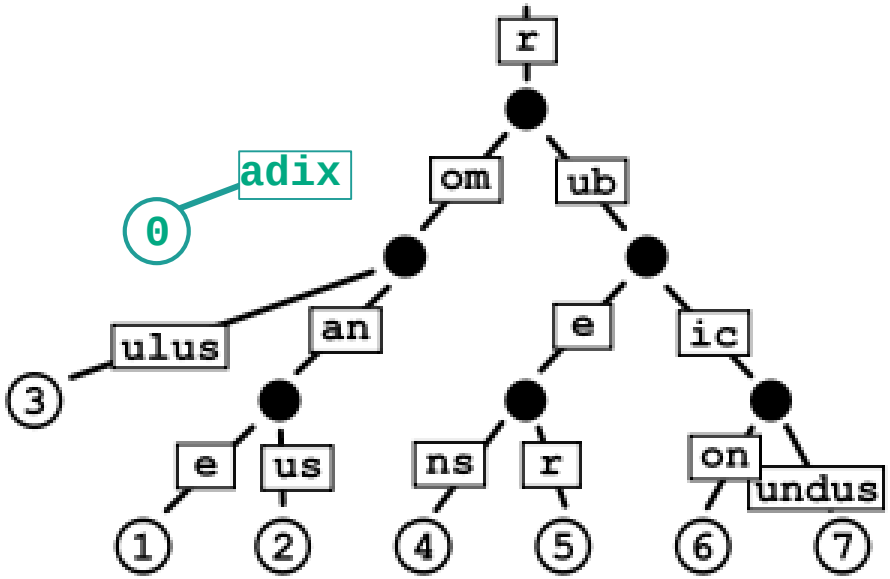

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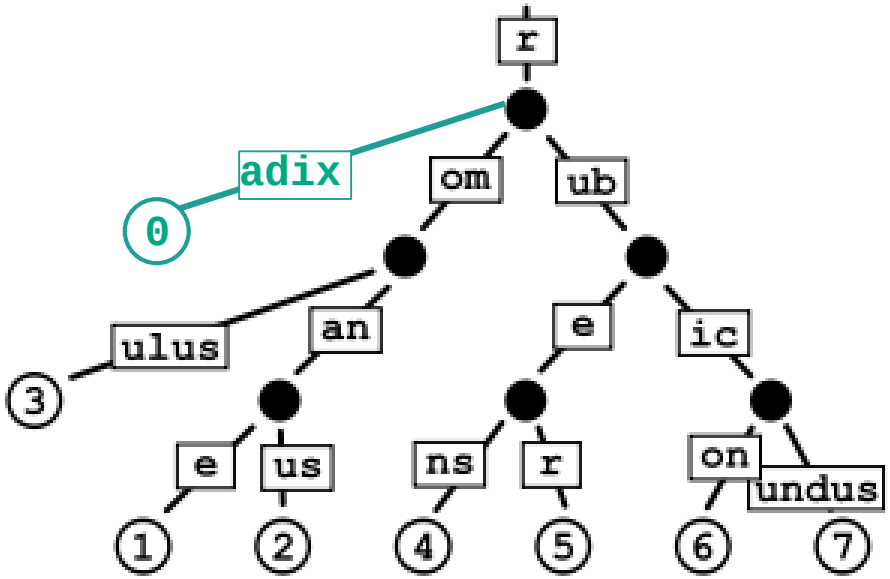

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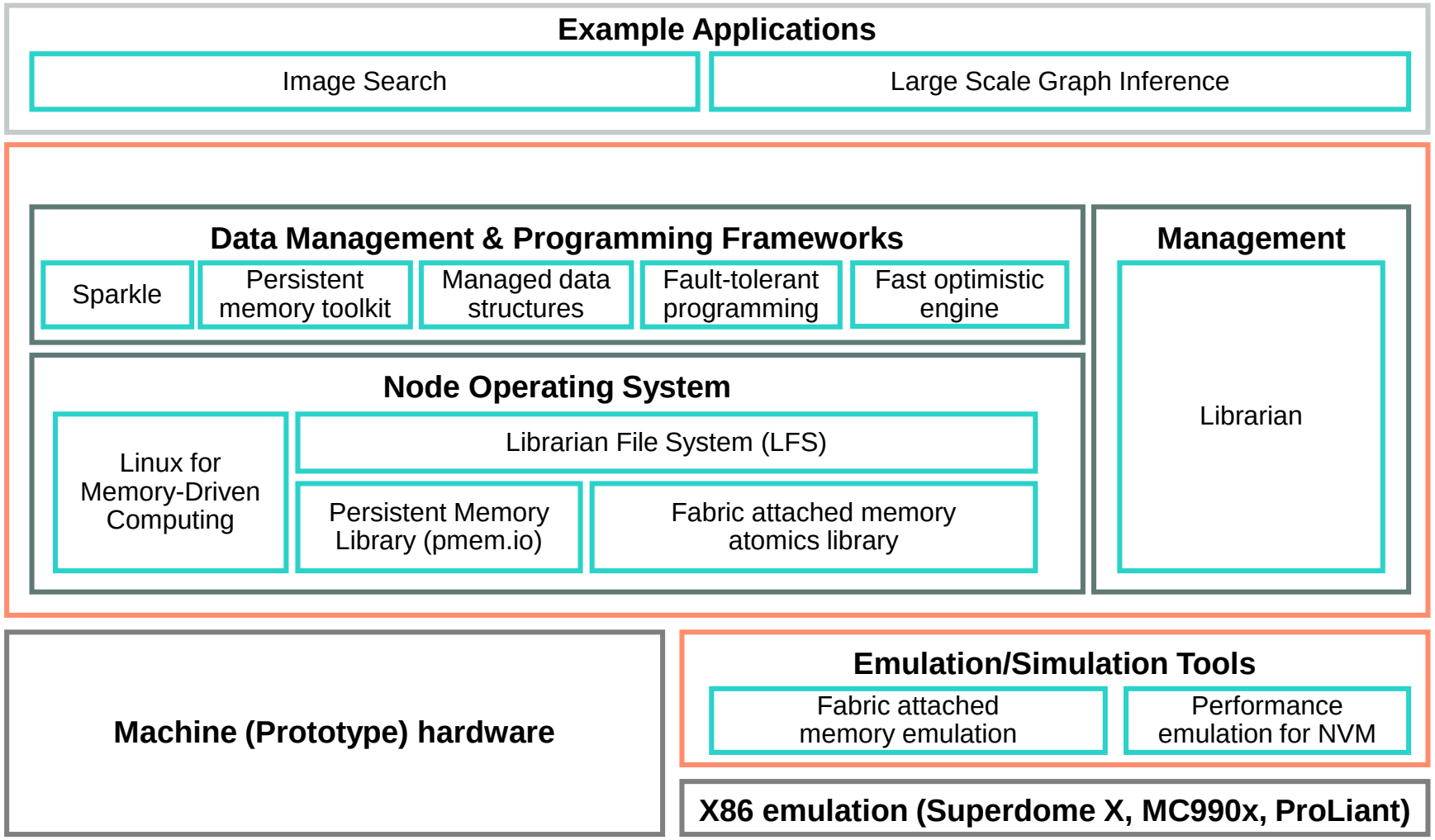
Memory-Driven Computing Developer Toolkit

Software already available to you



- Example applications
- Programming and analytics tools
- Operating system support
- Emulation/simulation tools

Get access to the toolkit:

https://www.labs.hpe.com/the-machine/developer-toolkit

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Open source components

Persistent memory as storage?

–If persistent memory is the new storage…

it must safely remember persistent data.

–Persistent data should be stored:

- Reliably, in the face of failures
- Securely, in the face of exploits
- In a cost-effective manner
- Using a data access API that's most natural for the device characteristics

Storing data reliably, securely and cost-effectively

The problem

- Potential concerns about using persistent memory to safely store persistent data:
  - NVM failures may result in loss of persistent data
  - Persistent data may be stolen

- Time to revisit traditional storage services
  - Ex: replication, erasure codes, encryption, compression, deduplication, wear leveling, snapshots

- New challenges:
  - Need to operate at *memory* speeds, not storage speeds
  - Traditional solutions (e.g., encryption, compression) complicate direct access
  - Space-efficient redundancy for NVM

Storing data reliably, securely and cost-effectively
Potential solutions

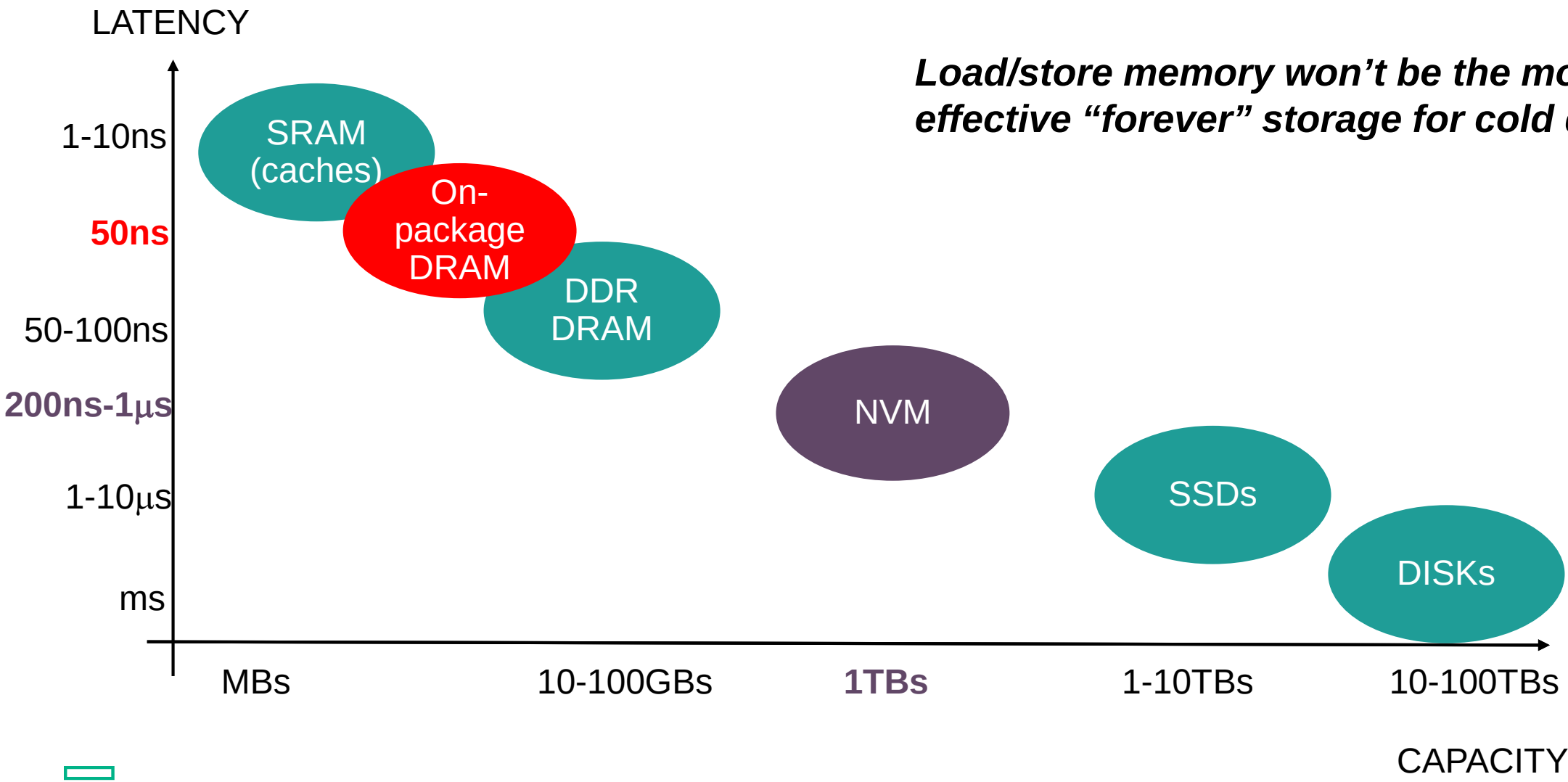
- Software implementations can trade performance for reliability, security and cost-effectiveness
  - But will diminish benefits from faster technologies

- Memory-side hardware acceleration
  - Memory speeds may demand acceleration (e.g., DMA-style data movement, memset, encryption, compression)
  - What functions are ripe for memory-side acceleration?

- Wear leveling for fabric-attached non-volatile memory
  - Repeated NVM writes may exacerbate device wear issues
  - What's the right balance between hardware-assisted wear leveling and software techniques?

- Fabric-attached non-volatile memory diagnostics
  - What is the equivalent of Self-Monitoring, Analysis and Reporting Technology (SMART) for NVM?

Memory + storage hierarchy technologies



Load/store memory won't be the most cost-effective "forever" storage for cold data

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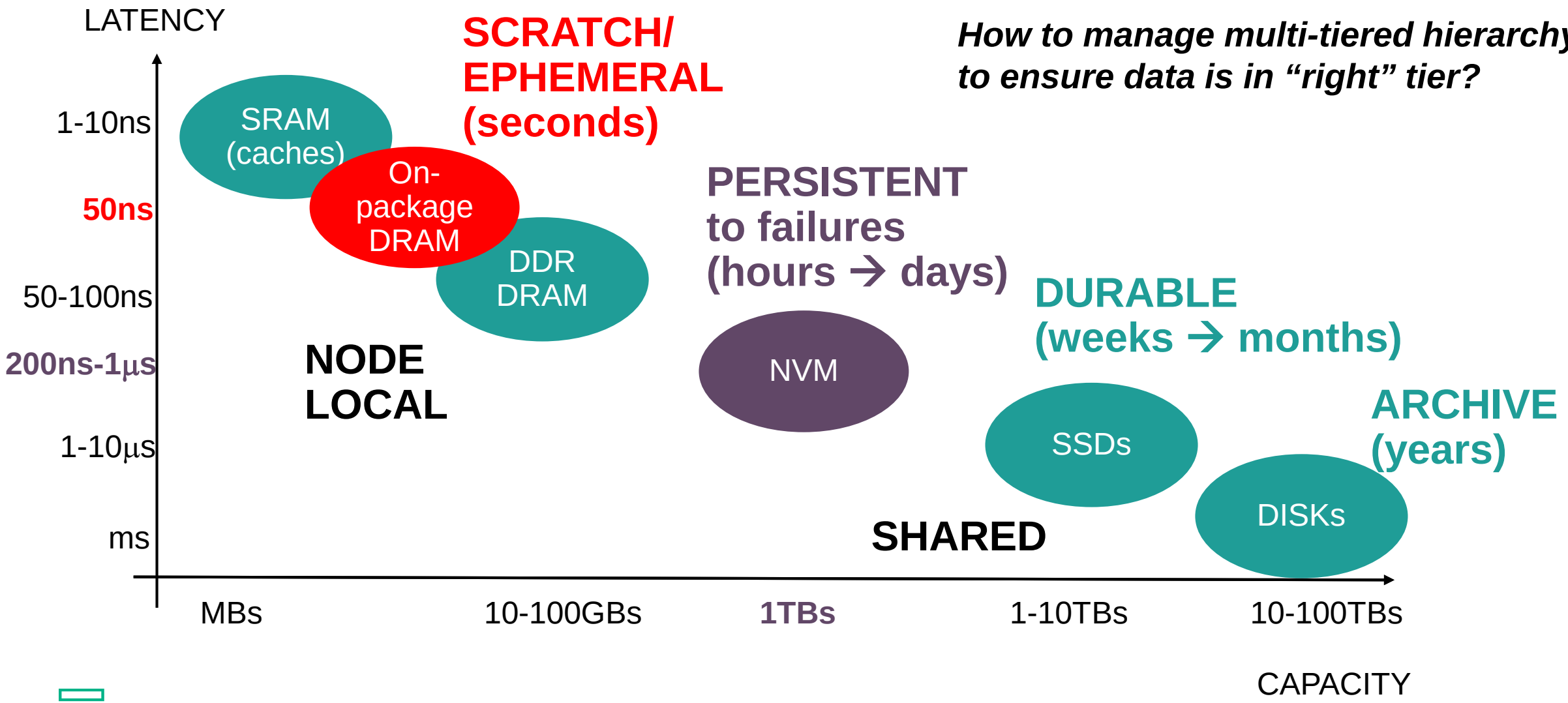
Memory + storage hierarchy – a usage view (ownership)



How to manage multi-tiered hierarchy, to ensure data is in "right" tier?

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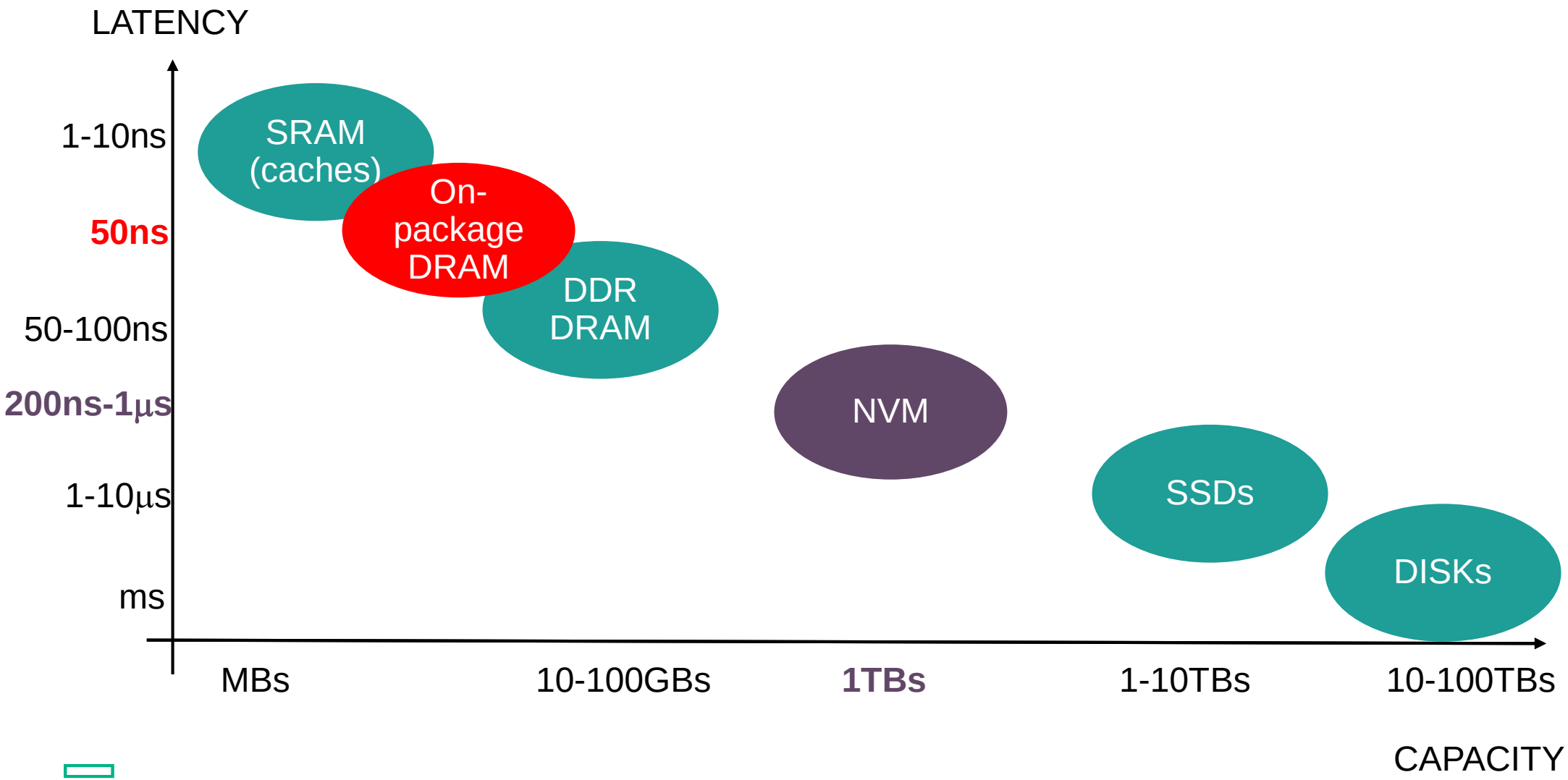
The appropriate API for the technology



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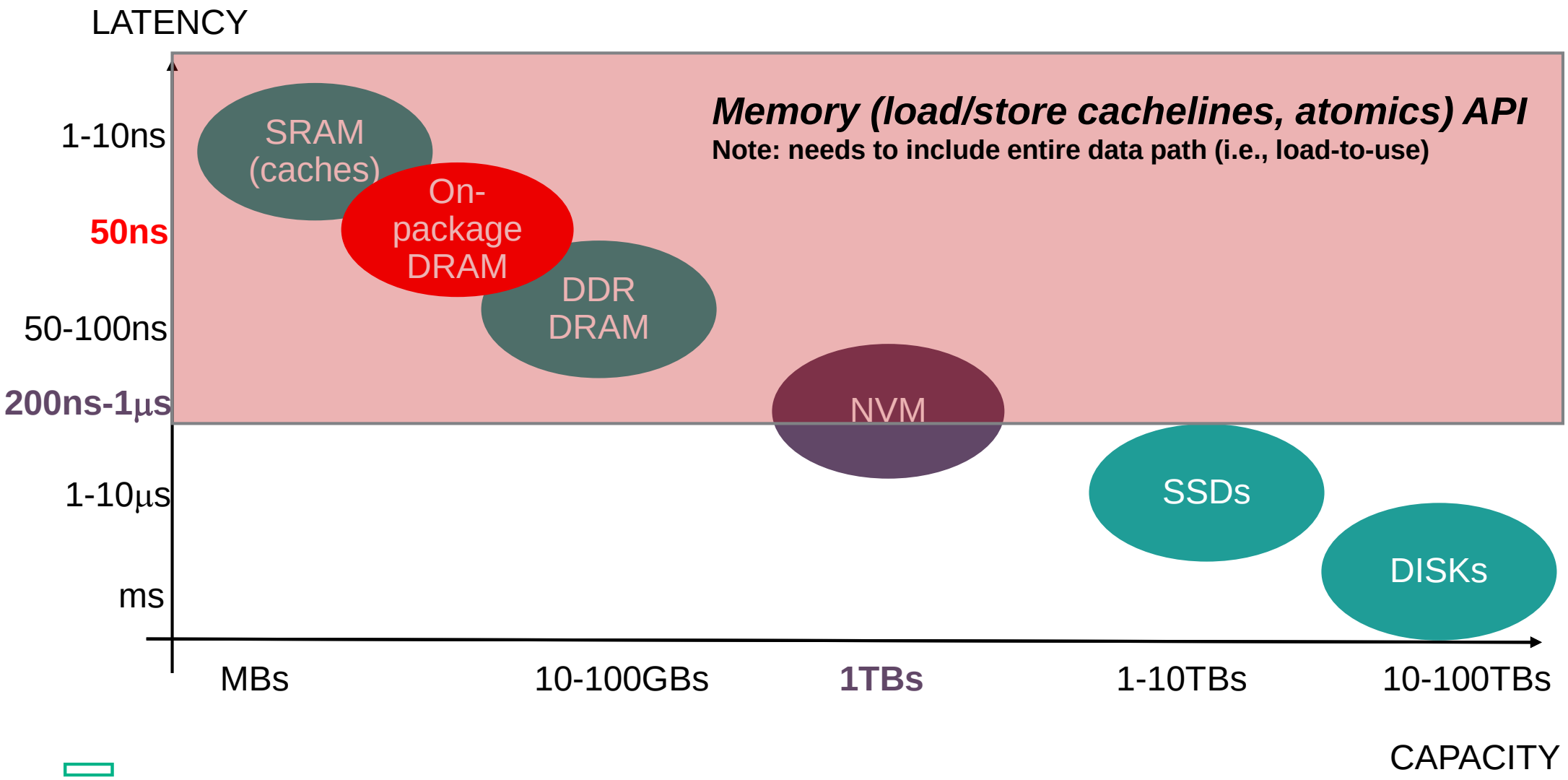

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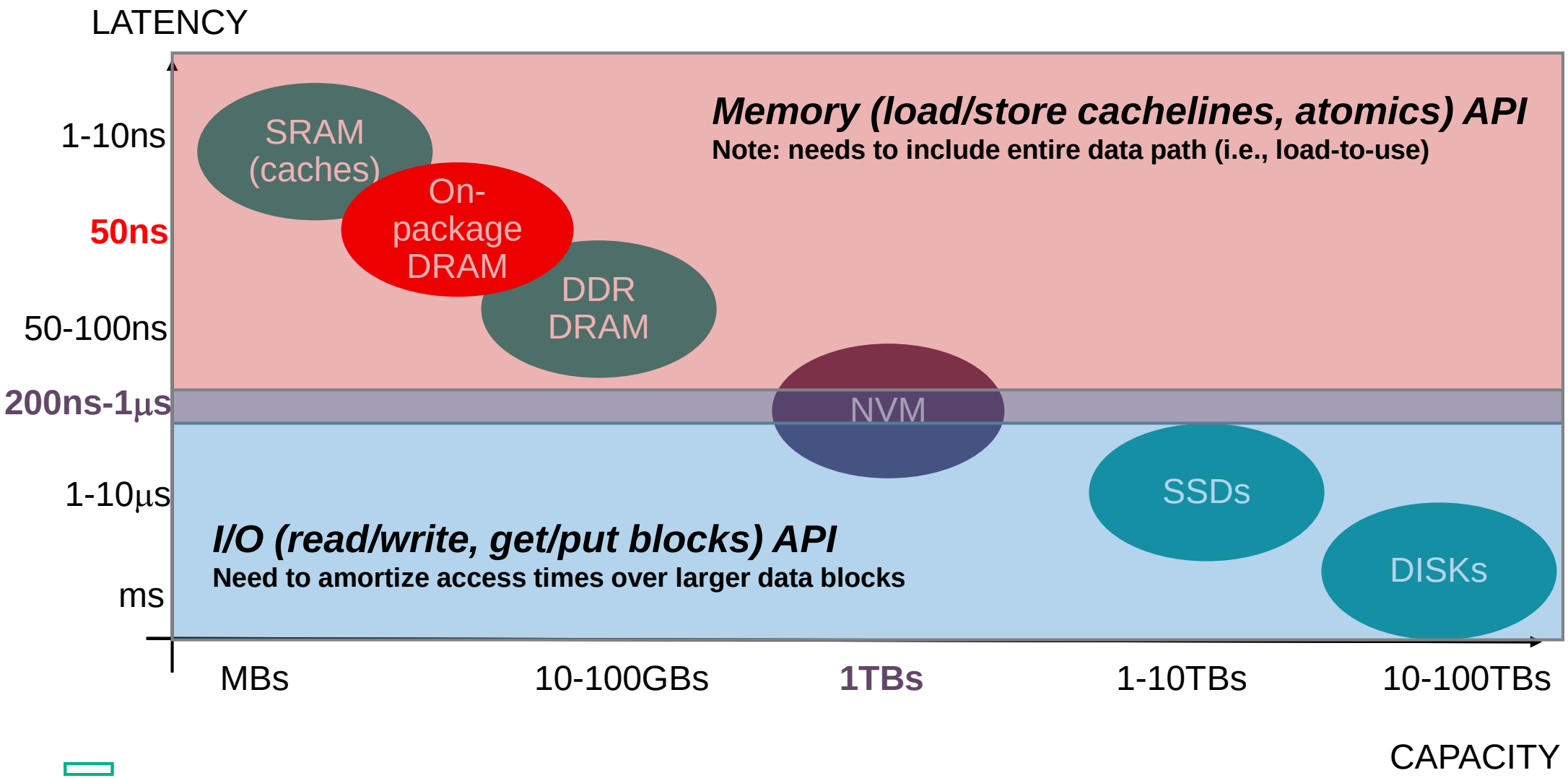

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How to get started with Memory-Driven Computing

- Latest updates on The Machine project and Memory-Driven Computing: www.hpe.com/themachine

- Join The Machine User Group at https://www.labs.hpe.com/the-machine/user-group
  - Join community discussions on Slack https://www.labs.hpe.com/slack #themachineusergroup
  - Subscribe to “The Machine User Group” tab in the “Behind the scenes @ Labs” blog https://community.hpe.com/t5/Behind-the-scenes-Labs/bg-p/BehindthescenesatLabs/label-name/The%20Machine%20User%20Group#.WXZGN4jyscE.
    Register and click “subscribe to this label”.
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Wrapping up

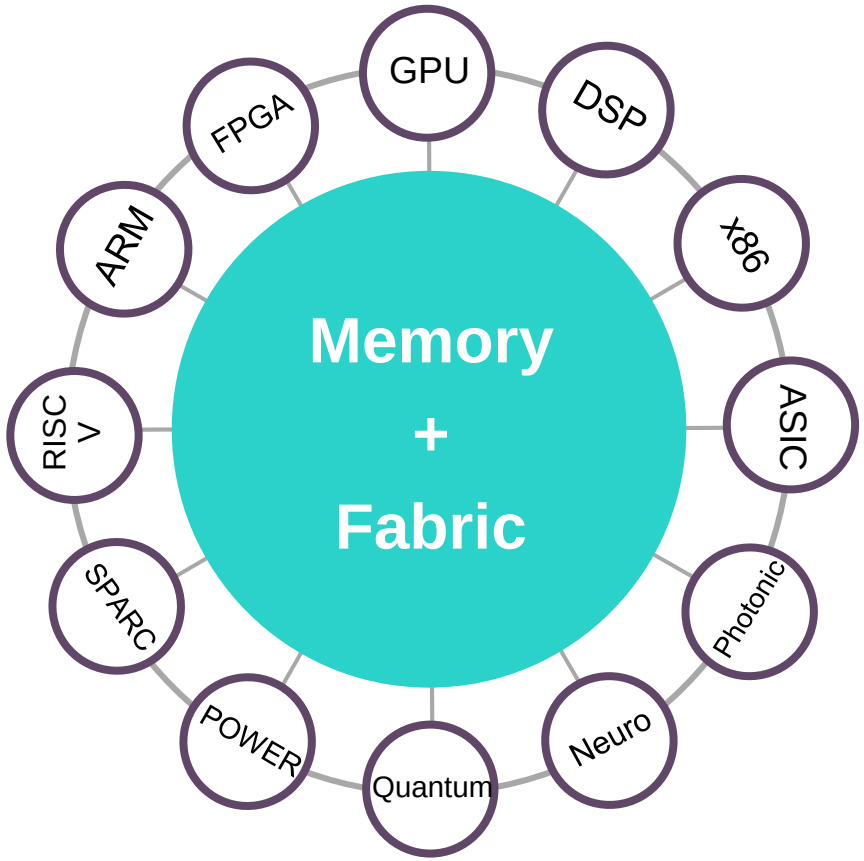
– Persistent memory blurs the line between memory and storage

– Gen-Z fabric enables us to shift system architecture towards Memory-Driven Computing

– Combination of technologies enables us to rethink the programming model
  – Simplify software stack
  – Operate directly on memory-format persistent data

– Many opportunities for software innovation

– How would *you* exploit Memory-Driven Computing?



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