Disaggregated & Heterogeneous Platform for Data Management

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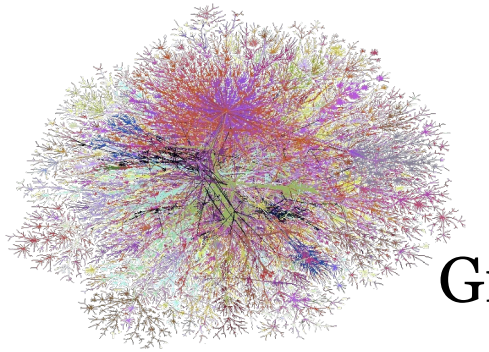
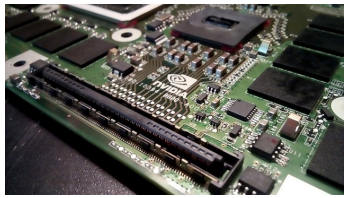
UNIVERSITY OF WATERLOO | DSG Data Systems Group

My research

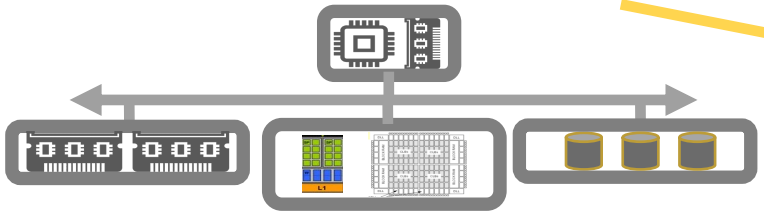


Graph Processing

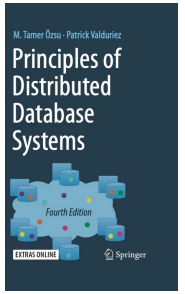


Graph Processing On GPUs[1,2]

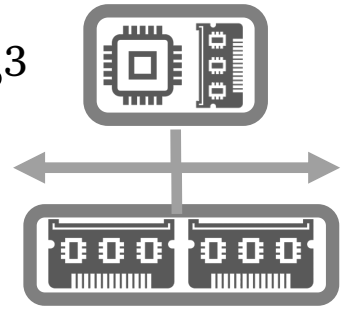
Graph Processing on Heterogeneous Platform



Distributed/Parallel Data Management



Disaggregated Systems[3]

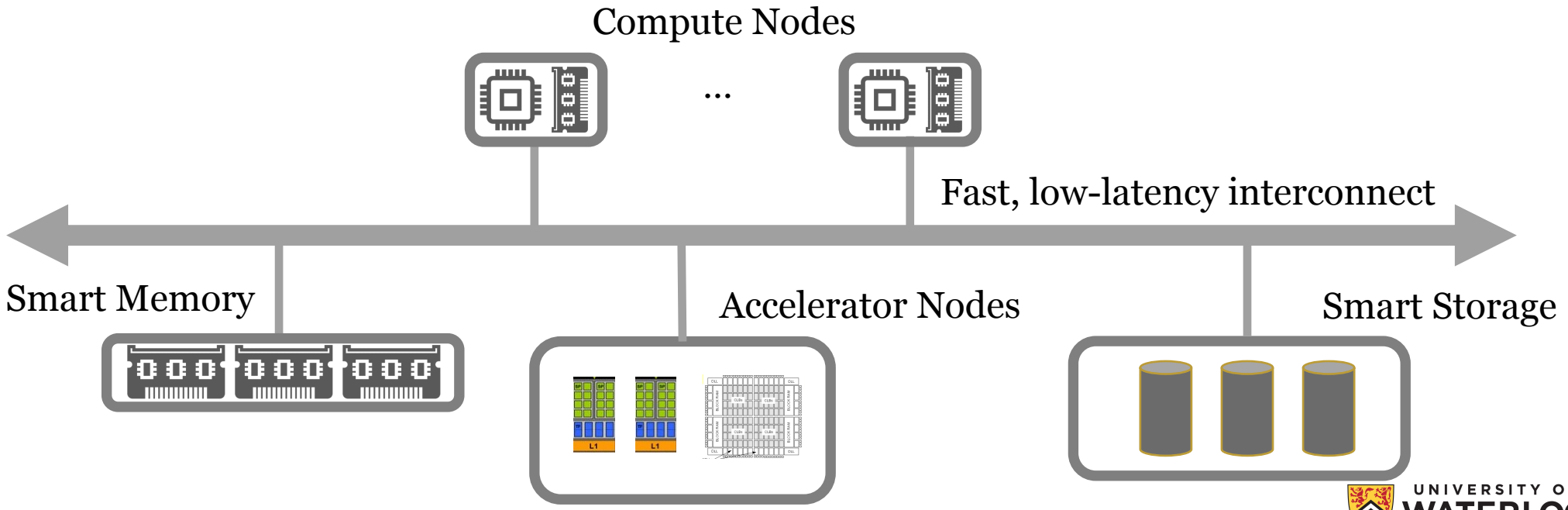


Graph Processing on Disaggregated Heterogeneous Platform

[1] L. Hu, L. Zou and M. T. Özsu. GAMMA: A Graph Pattern Mining Framework for Large Graphs on GPU, *Proc. ICDE*, 2023.
[2] L. Zeng, et al. GSI:GPU-friendly Subgraph Isomorphism, *Proc. ICDE*, 2020.
[3] R.Wang et al. The Case for Shared-Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

Disaggregated Heterogeneous Platform

- Disaggregated
  - Separate components with a fast interconnect
- Heterogeneous
  - "Executing programs on a computing platform with computing nodes of different characteristics."[1]



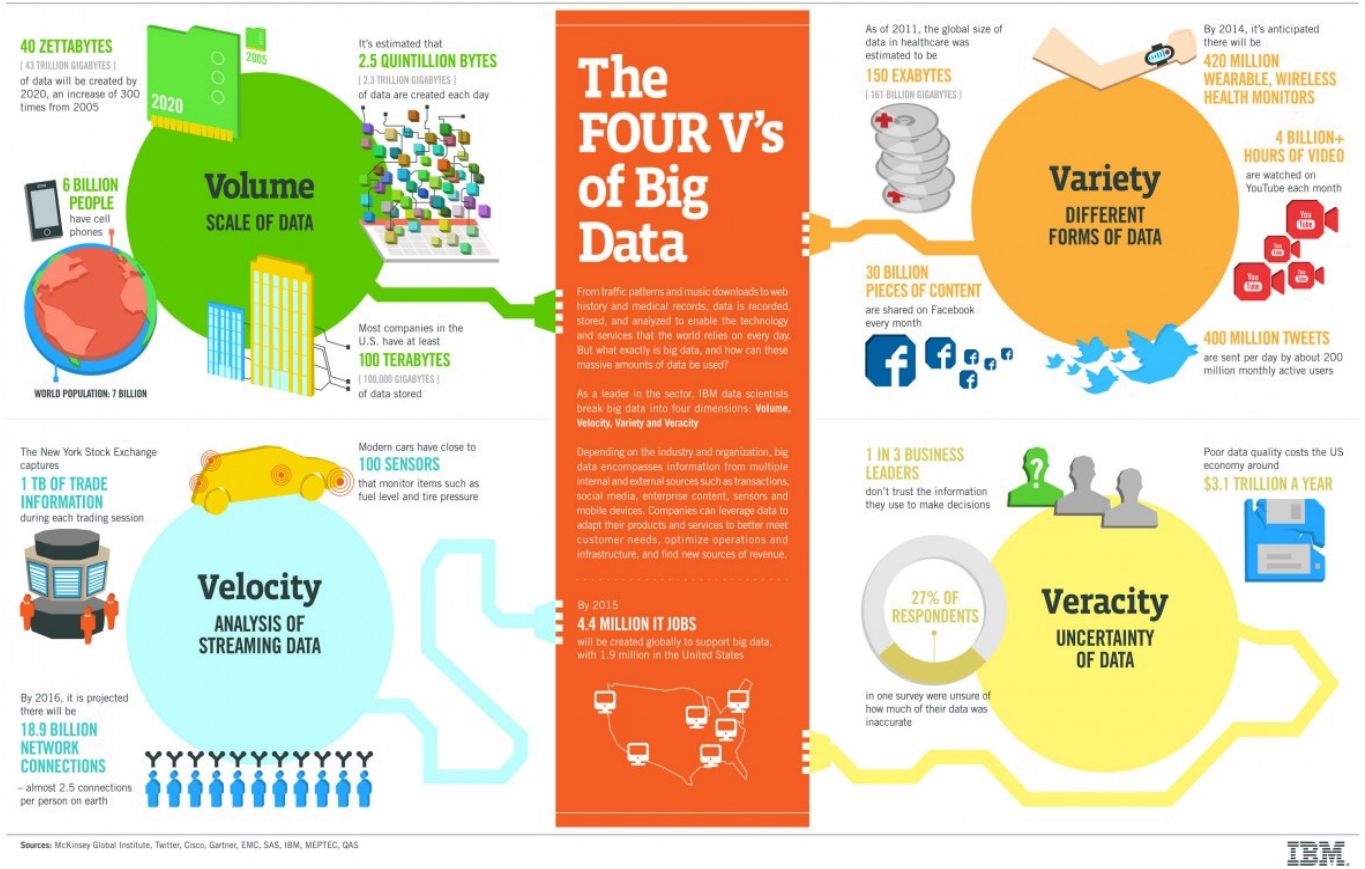
[1] M. Zahran. *Heterogeneous Computing*, ACM Books, 2019.

Why?

New Application Demands Technological Changes

New Application Demands

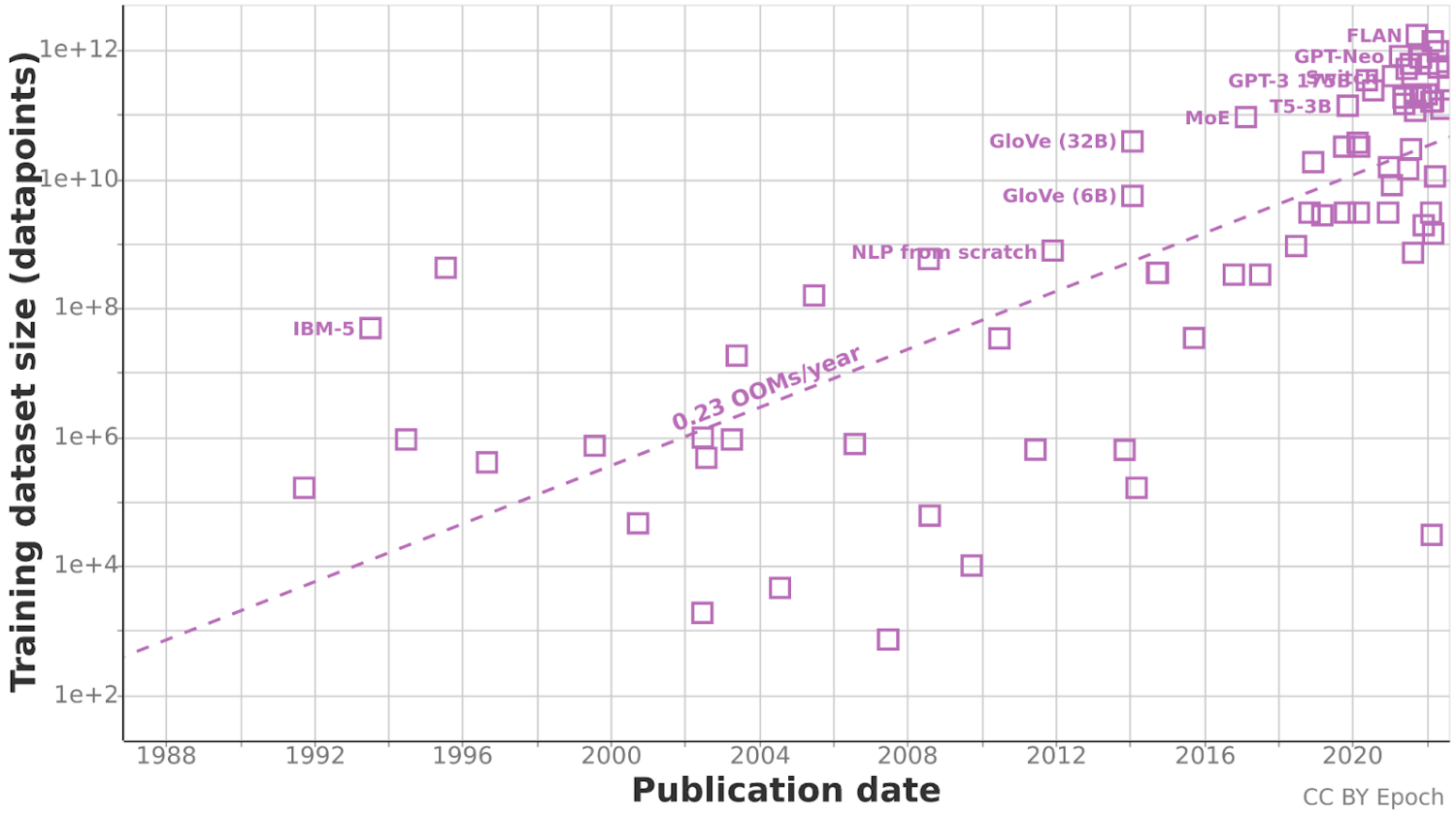
Big data applications



New Application Demands

Big data applications

- Very large storage
  - 10x rule in ML workloads



https://epochai.org/blog/trends-in-training-dataset-sizes

New Application Demands

Big data applications

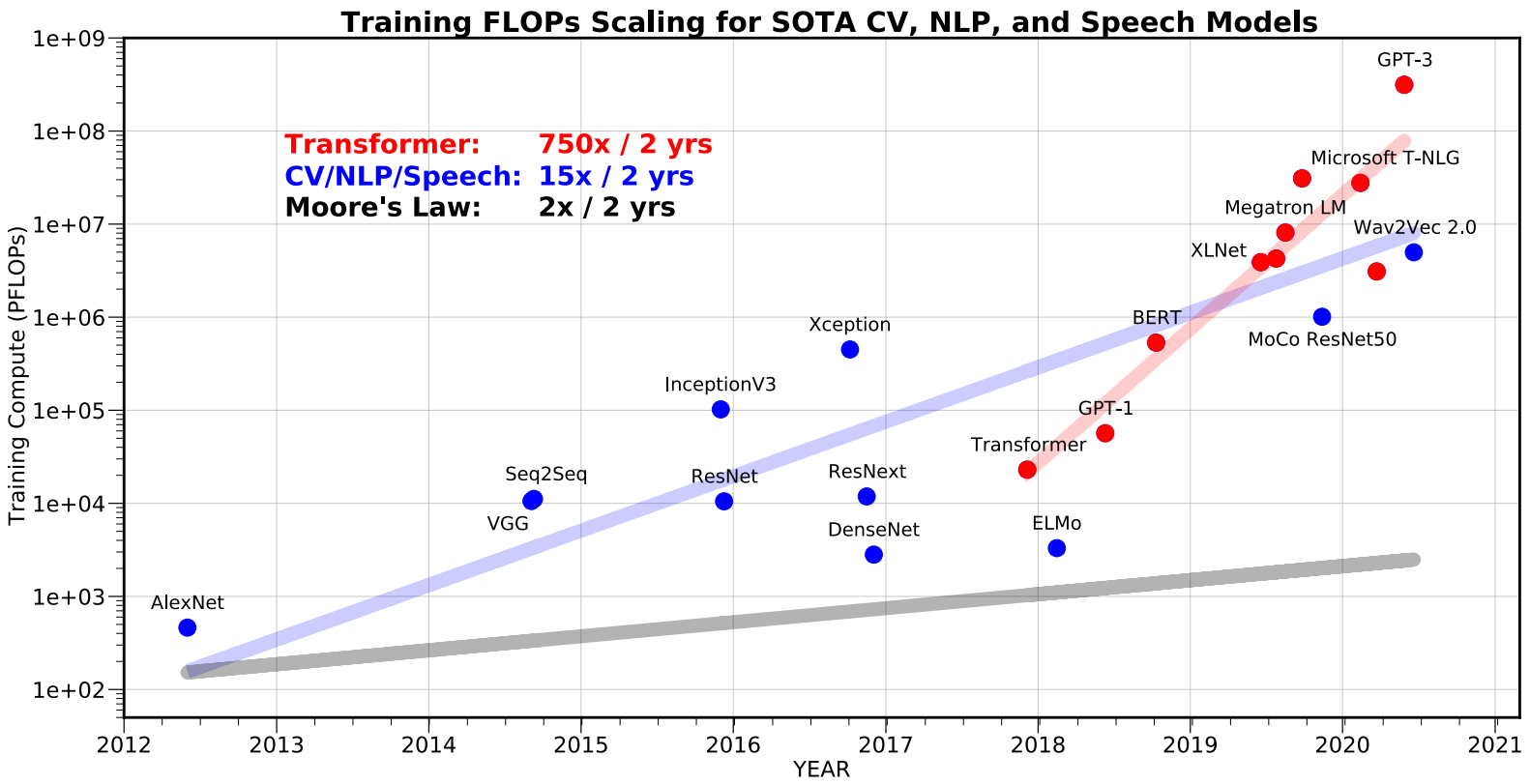
- Very large storage
  - 10x rule in ML workloads
- Repetitive computation

```
class Vertex:
    def __init__(self, name):
        self.name = name
        self.children = []
        self.parents = []
        self.auth = 1.0
        self.hub = 1.0
        self.pagerank = 1.0

#One iteration computation
def PageRank_one_iter(graph, d):
    vertex_list = graph.vertices
    for vertex in vertex_list:
        vertex.update_pagerank(d, len(graph.vertices))

#Go over all vertices until convergence
def PageRank(graph, d):
    finished = False
    while not finished:
        PageRank_one_iter(graph, d)
        finished = converge()
```

New Application Demands

Big data applications

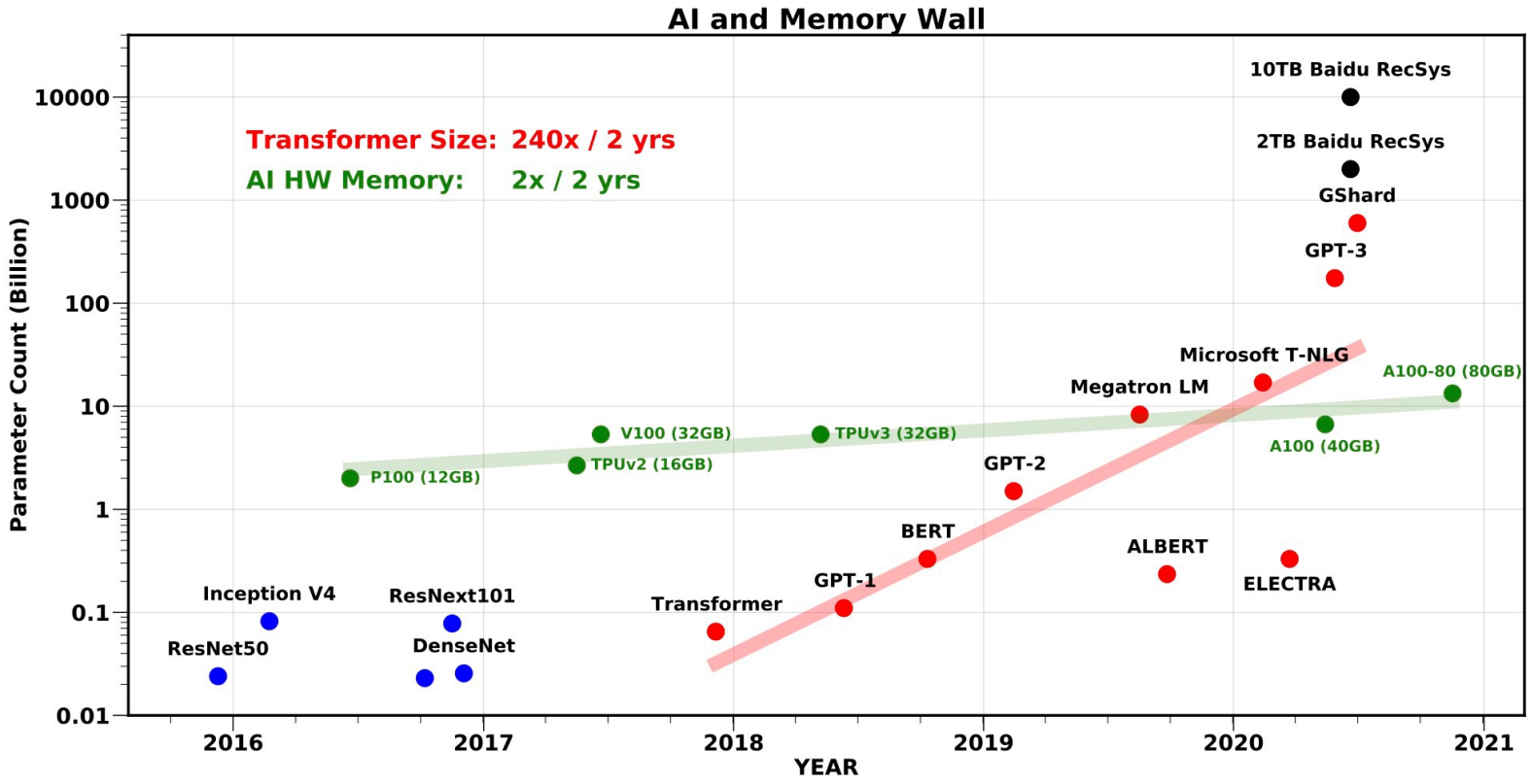
- Very large storage
  - 10x rule in ML workloads
- Repetitive computation
  - Excessive computing cycles



New Application Demands

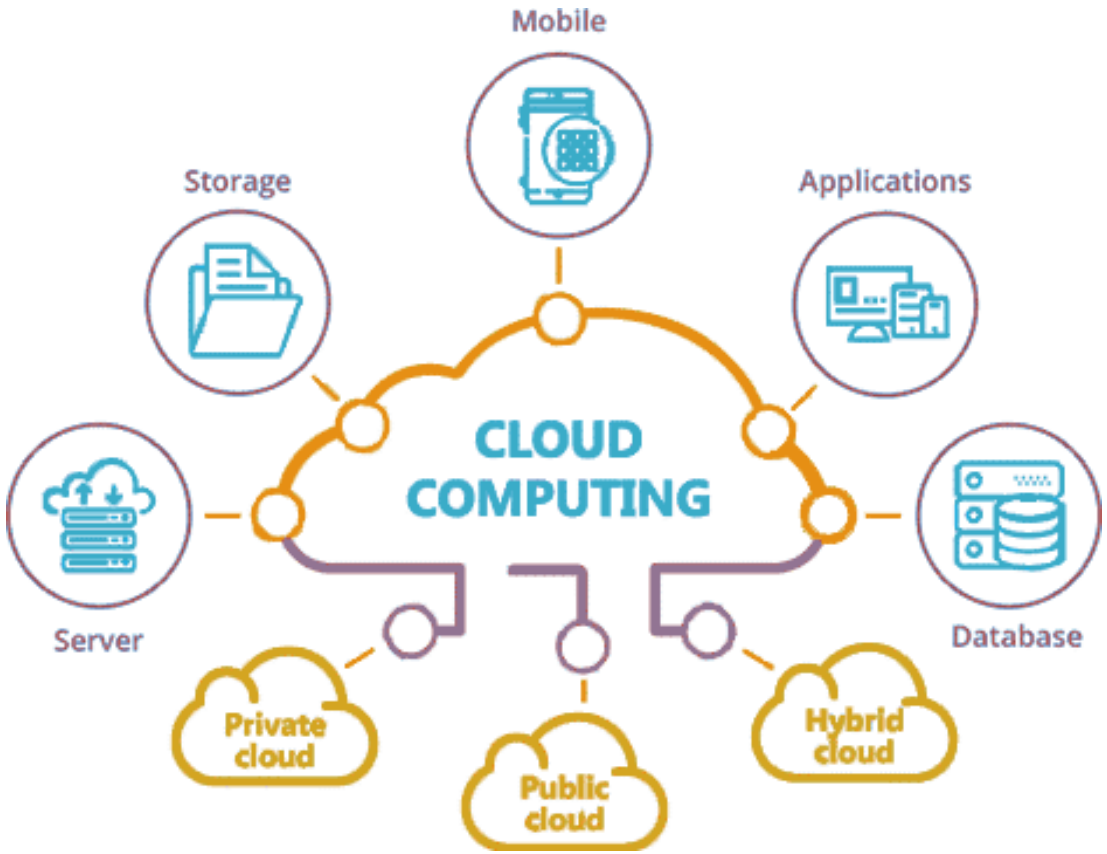
Big data applications

- Very large storage
  - 10x rule in ML workloads
- Repetitive computation
  - Excessive computing cycles
- Large memory



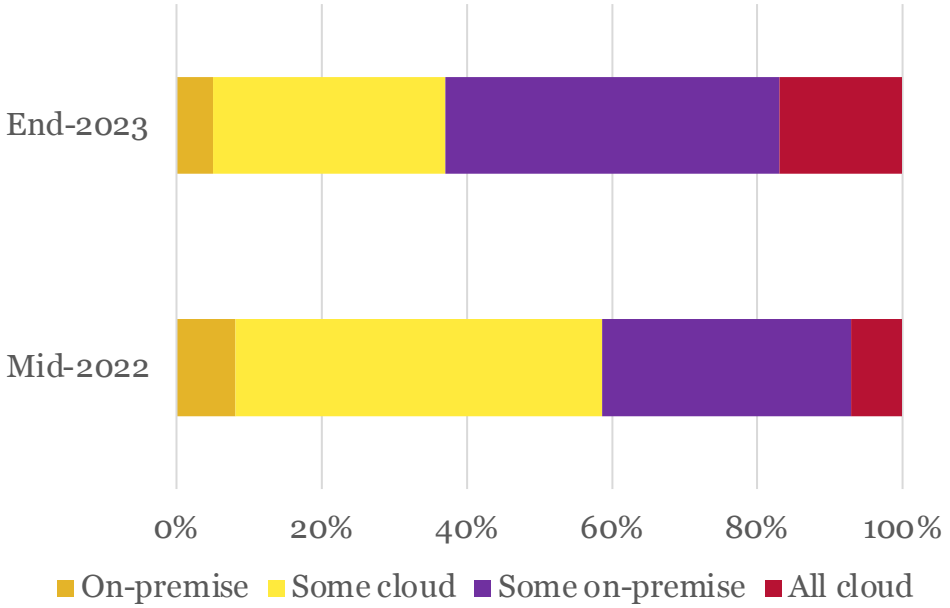
TECHNOLOGY CHANGES

Move to the Cloud

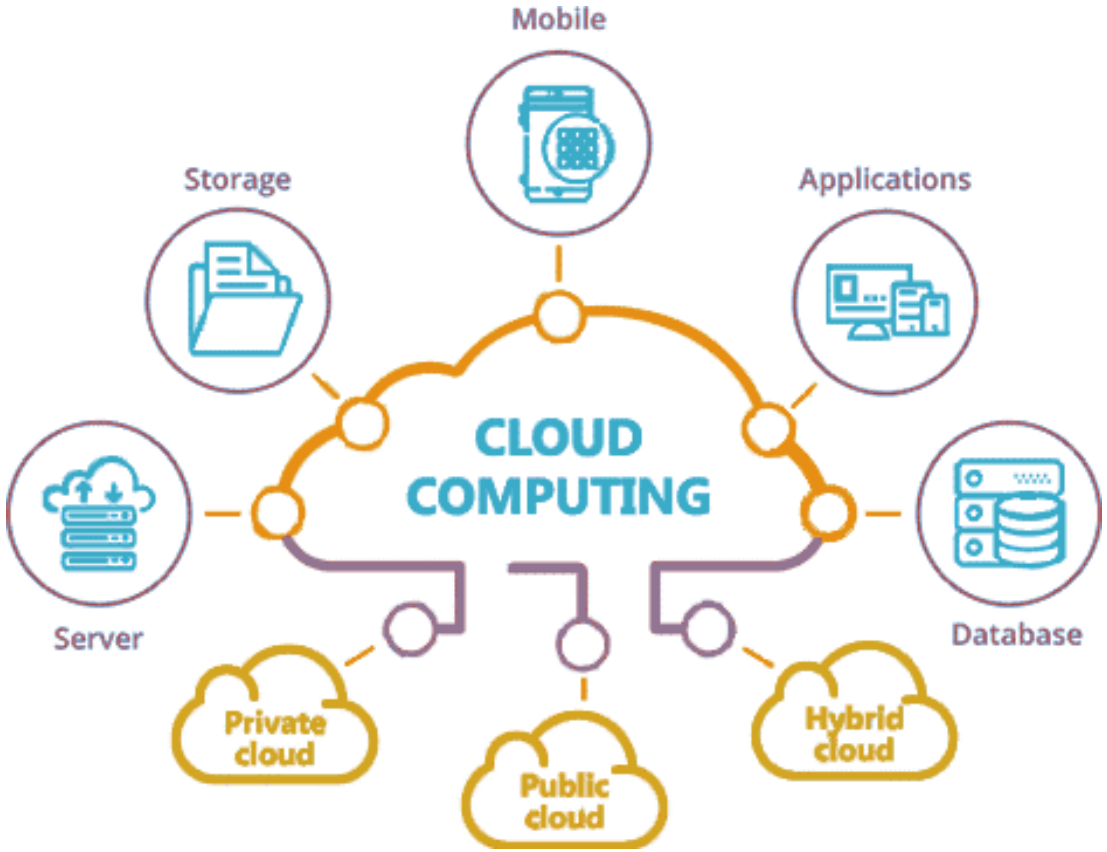


Move to the Cloud

- Move is expanding

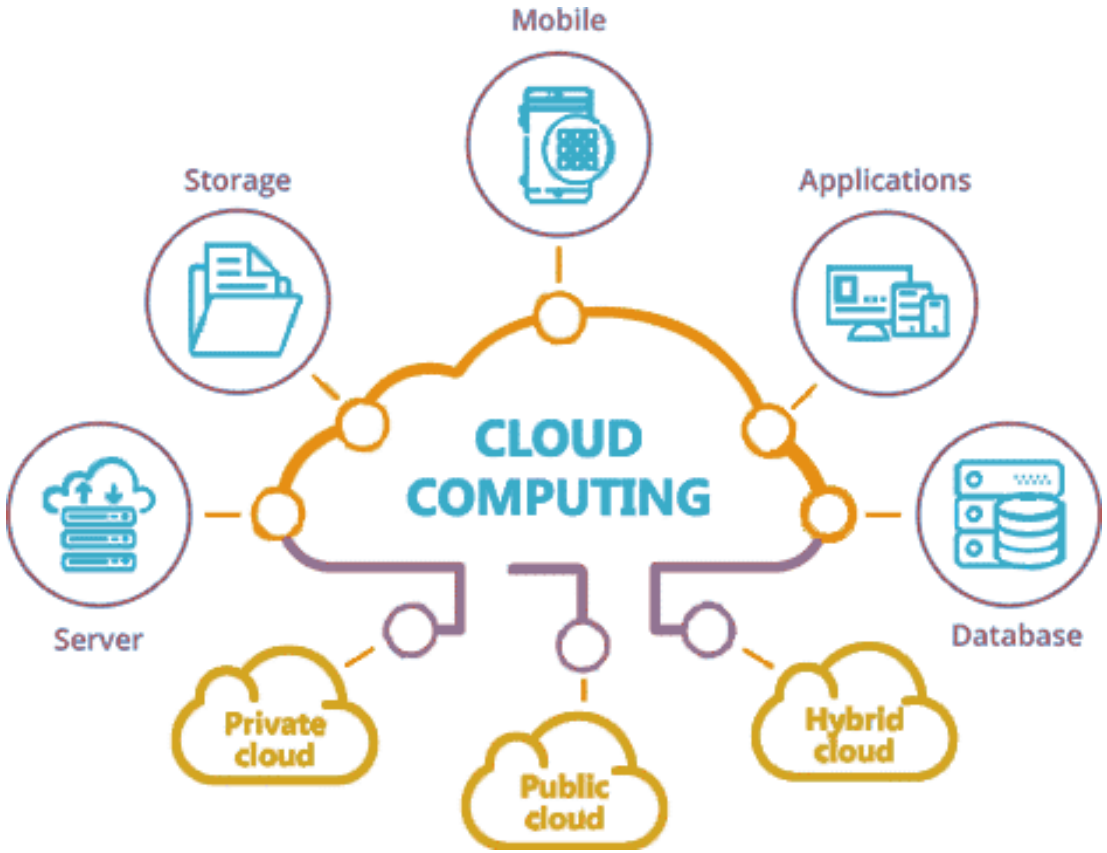


Foundry Cloud Computing Study, 2022



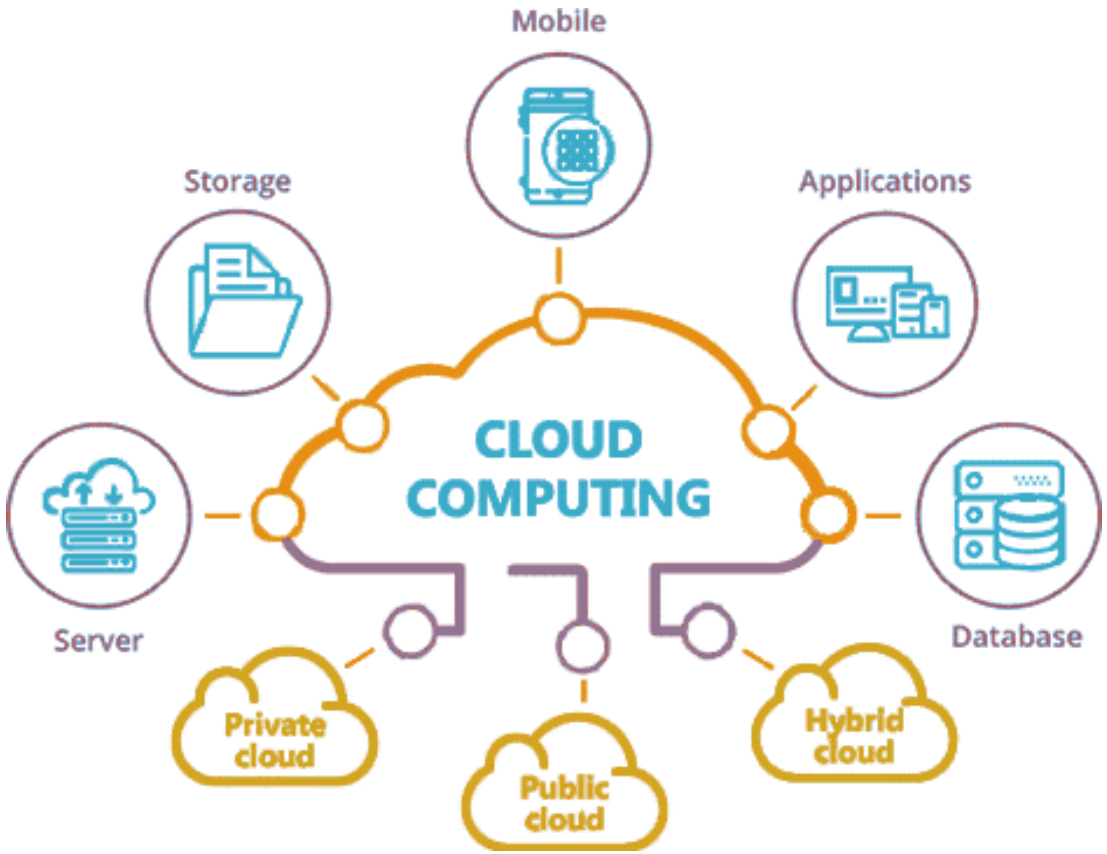
Move to the Cloud

- Move is expanding
- Reasons
  - Elasticity
  - Availability
  - Cost savings
  - …

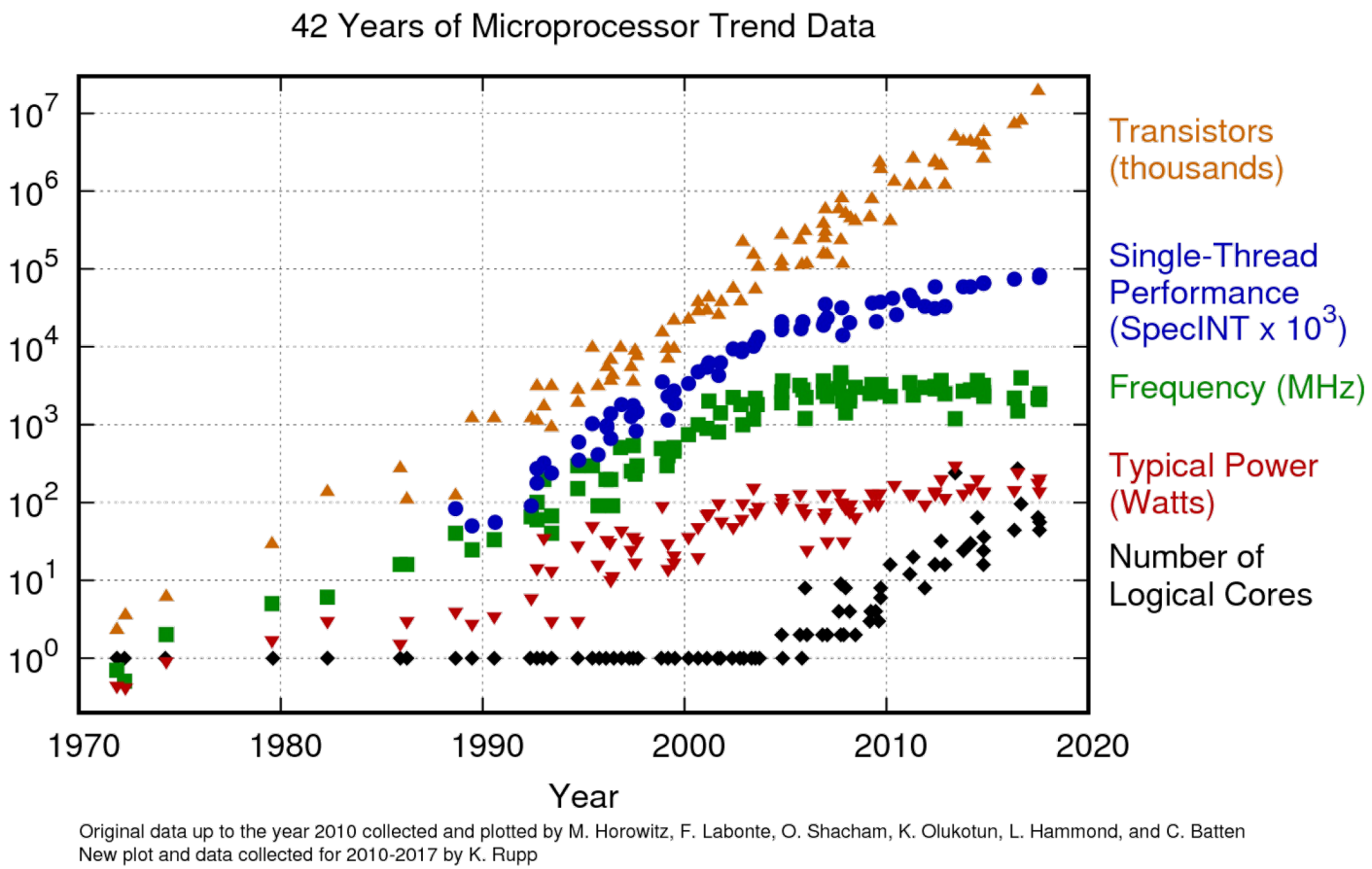


Move to the Cloud

- Move is expanding
- Reasons
  - Elasticity
  - Availability
  - Cost savings
  - …
- Stress points
  - Elasticity in demand
  - Configuration to meet SLAs
  - …



Is Traditional Processor Keeping Up?

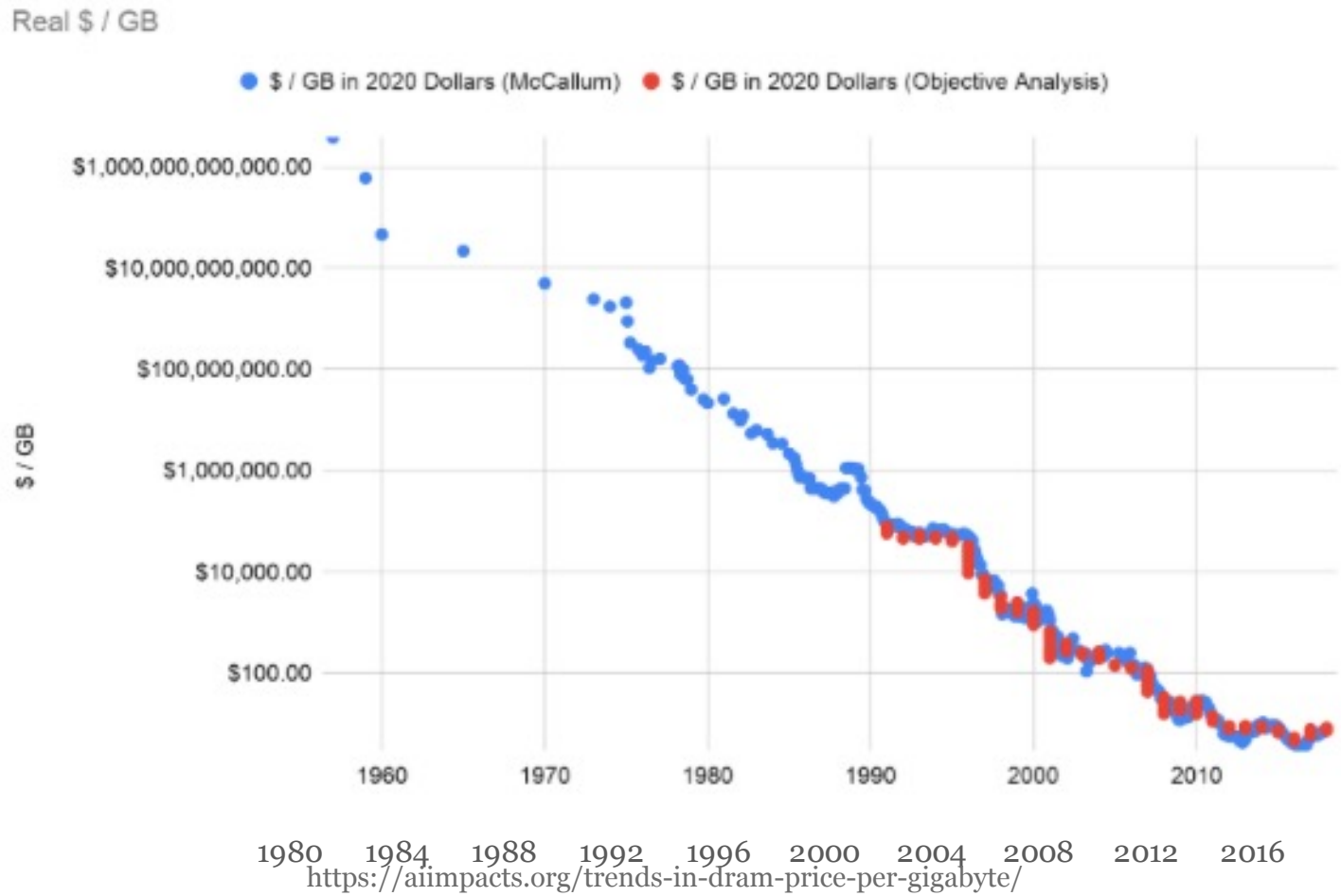


https://www.karlrupp.net/2015/06/40-years-of-microprocessor-trend-data/

- Moore's Law application questionable
  - *The number of transistors on a microchip doubles every two years*
- Pollack's Rule
  - *Microprocessor performance increase due to microarchitecture advances is roughly proportional to the square root of the increase in complexity.*

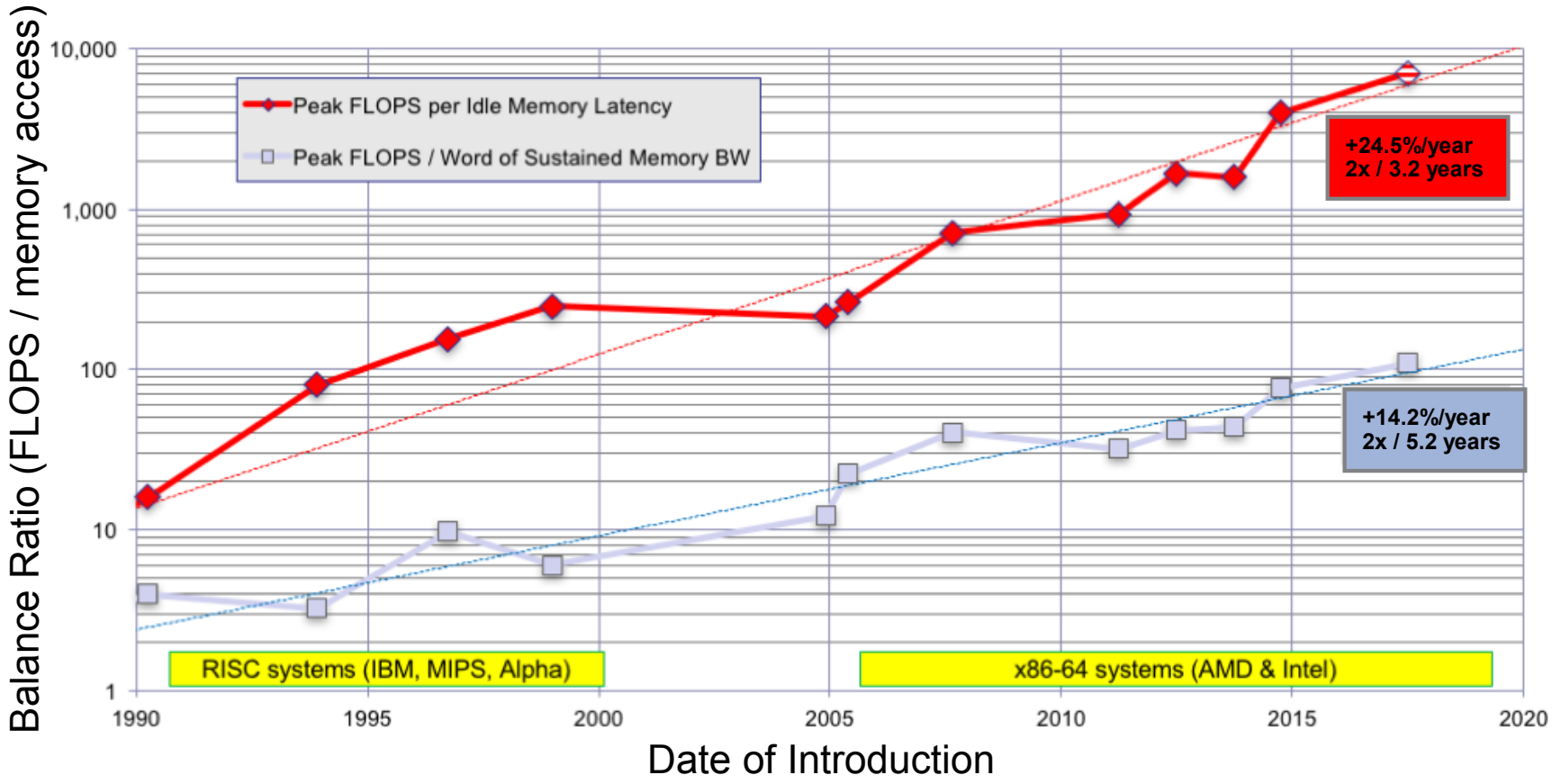
Changes in RAM

- RAM capacities increasing 10x every four years (?)
  - Not single memory chip
- RAM prices are going down
- Memory bandwidth increasing ~23% per year[1]
- Memory latency **increasing** ~4% per year[1]



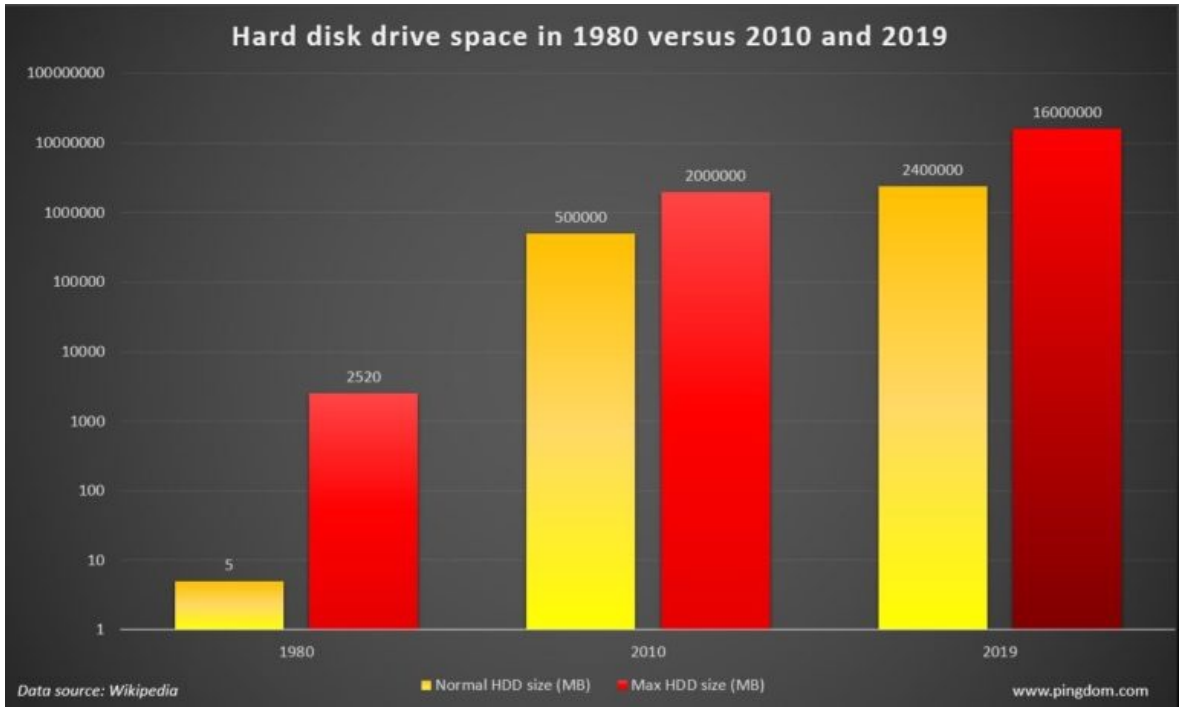
J. McCalpin. Memory Bandwidth and System Balance in HPC Systems: 2021 Update, Talk at Erlangen National High Performance Computing Center. https://hpc.fau.de/files/2021/12/memorybw_systembalance_slides_2021-12-15.pdf

Is The Memory Keeping Up?

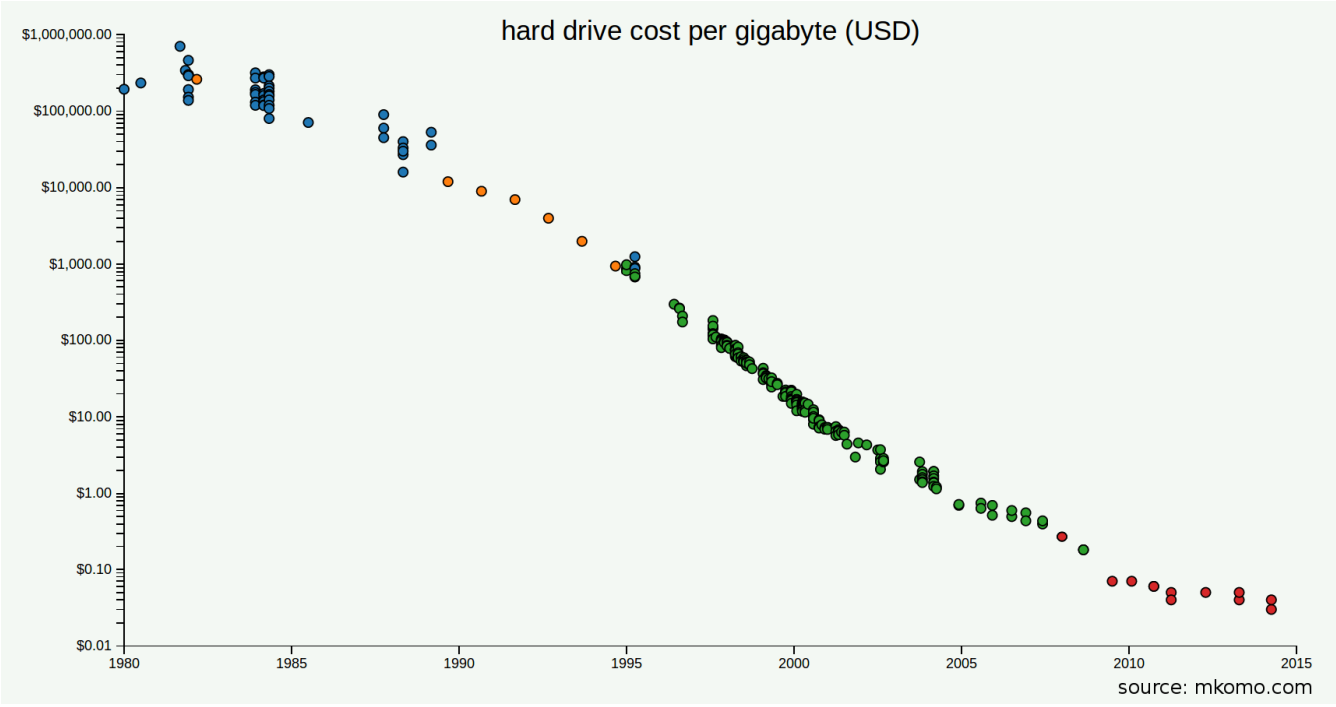


J. McCalpin. Memory Bandwidth and System Balance in HPC Systems, Invited talk at Supercomputing Symposium, 2016.
http://sites.utexas.edu/jdm4372/2016/11/22/sc16-invited-talk-memory-bandwidth-and-system-balance-in-hpc-systems/

Storage Capacity and Price Over Time



https://www.pingdom.com/



https://aiimpacts.com/

Storage Devices

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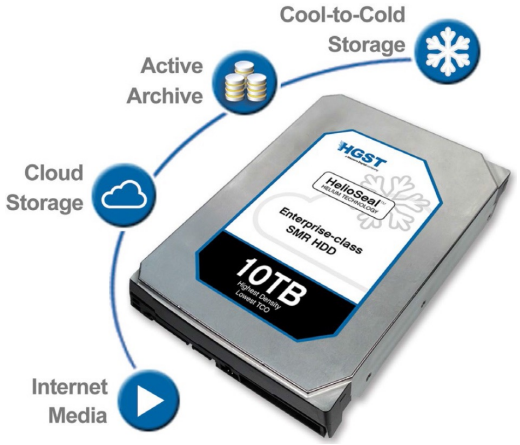

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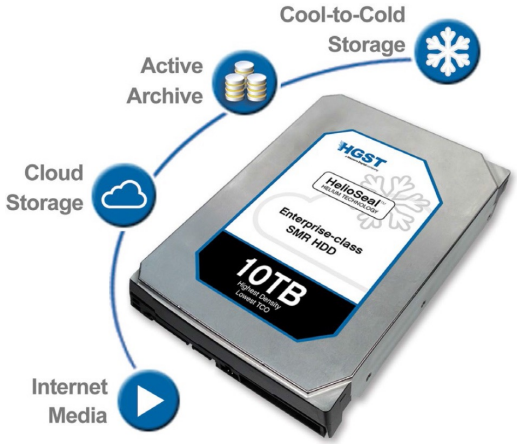

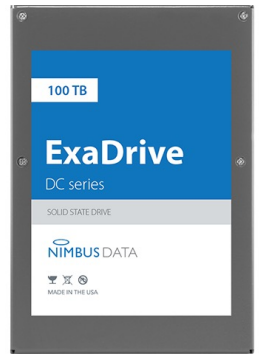

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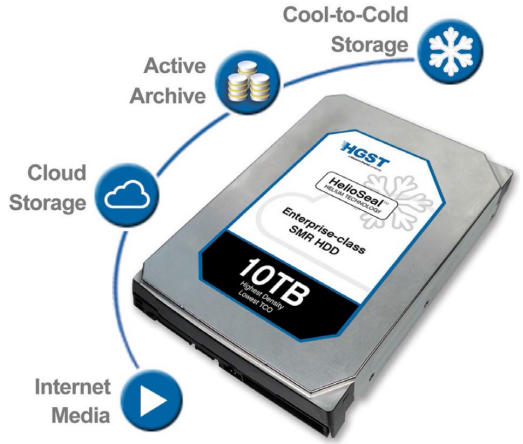
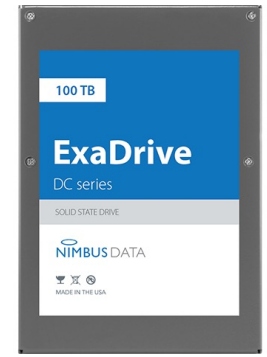
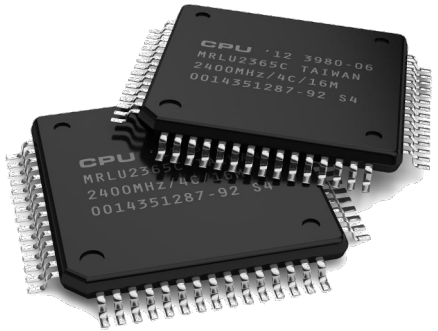
  - 1TB flash is common
  - Different storage hierarchy







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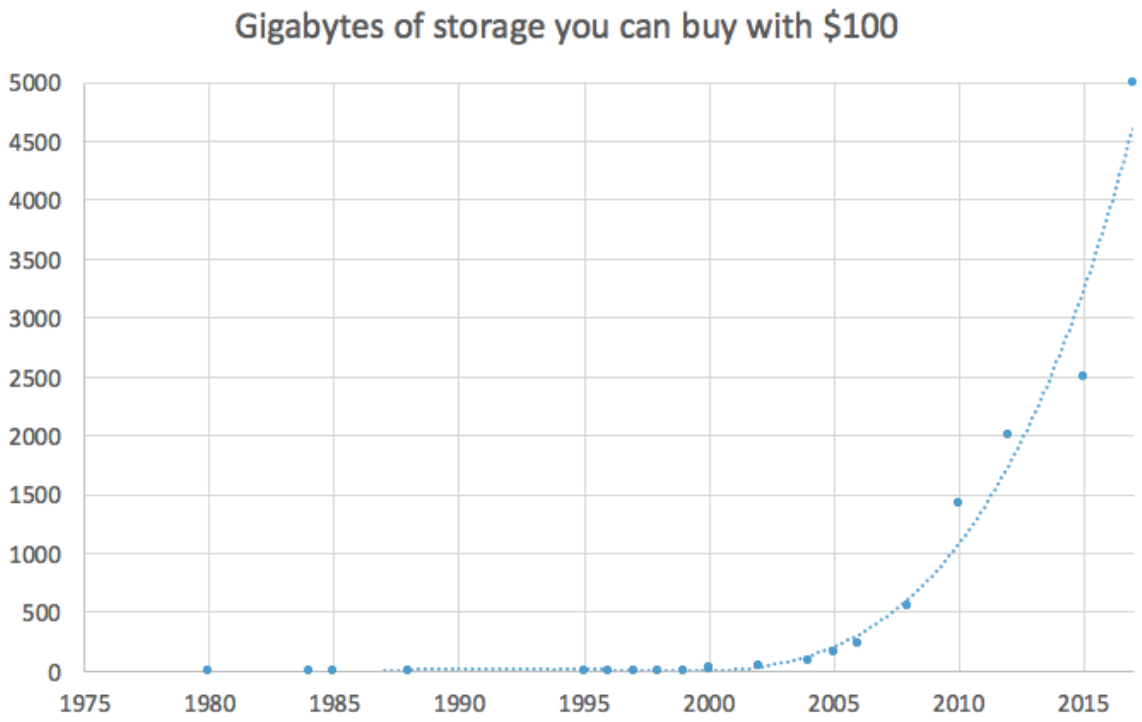
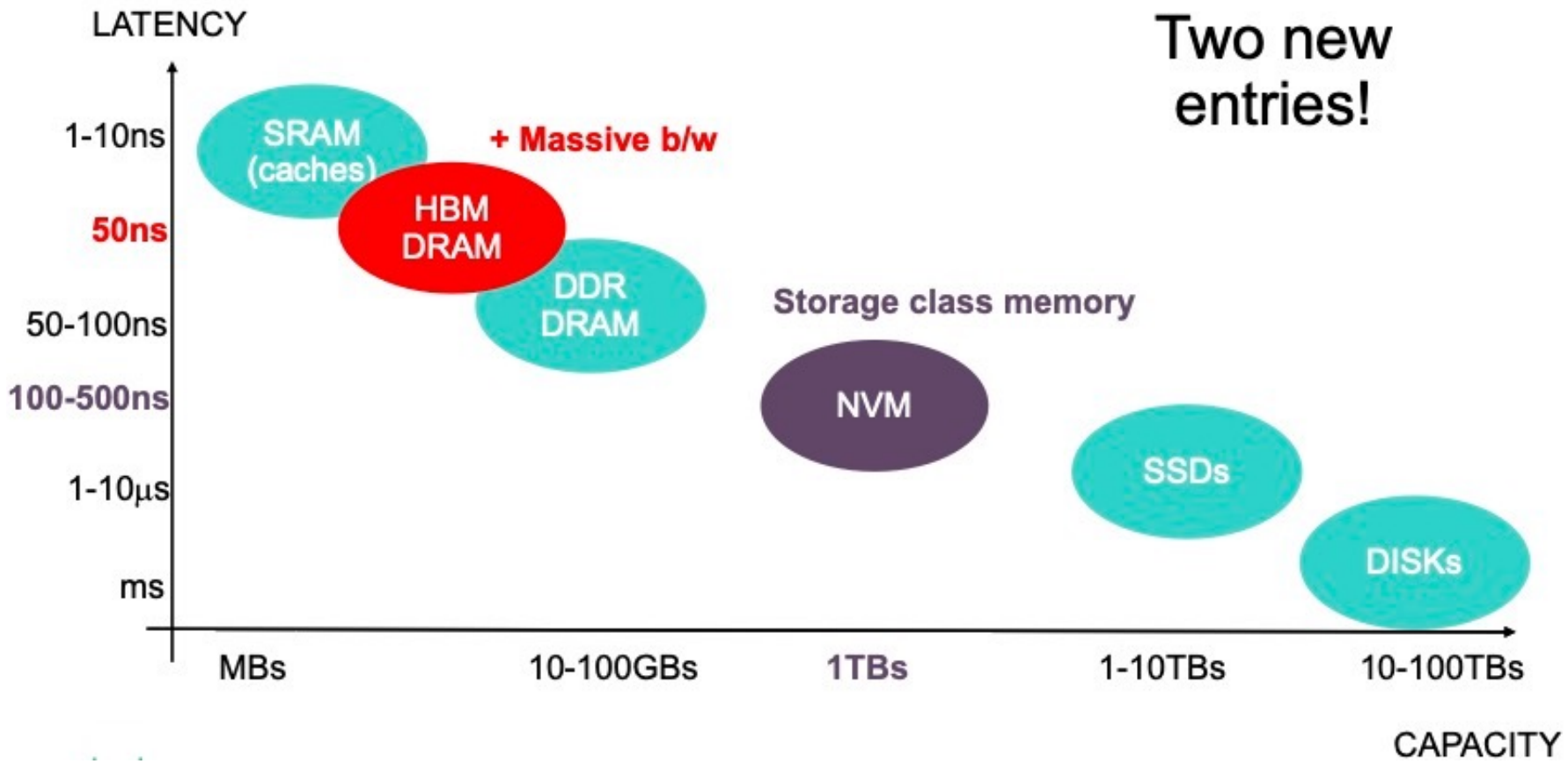
  - Different storage hierarchy
- Money goes a long way



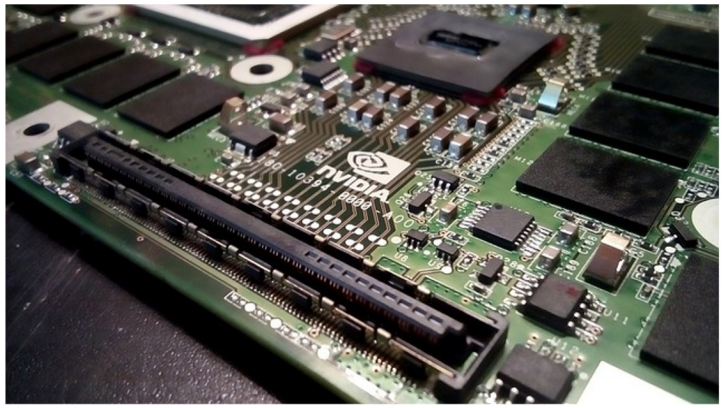
Changing Memory+Storage Hierarchy

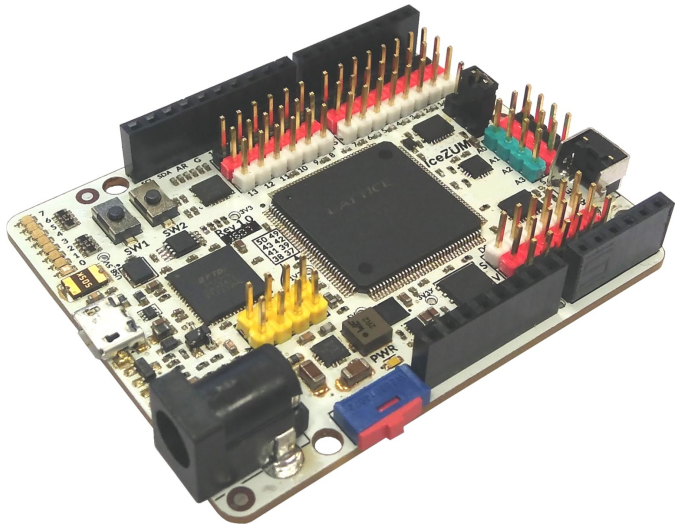


K. Keeton. Memory-Driven Computing, *Proc. USENIX FAST*, 2017.

Accellerators

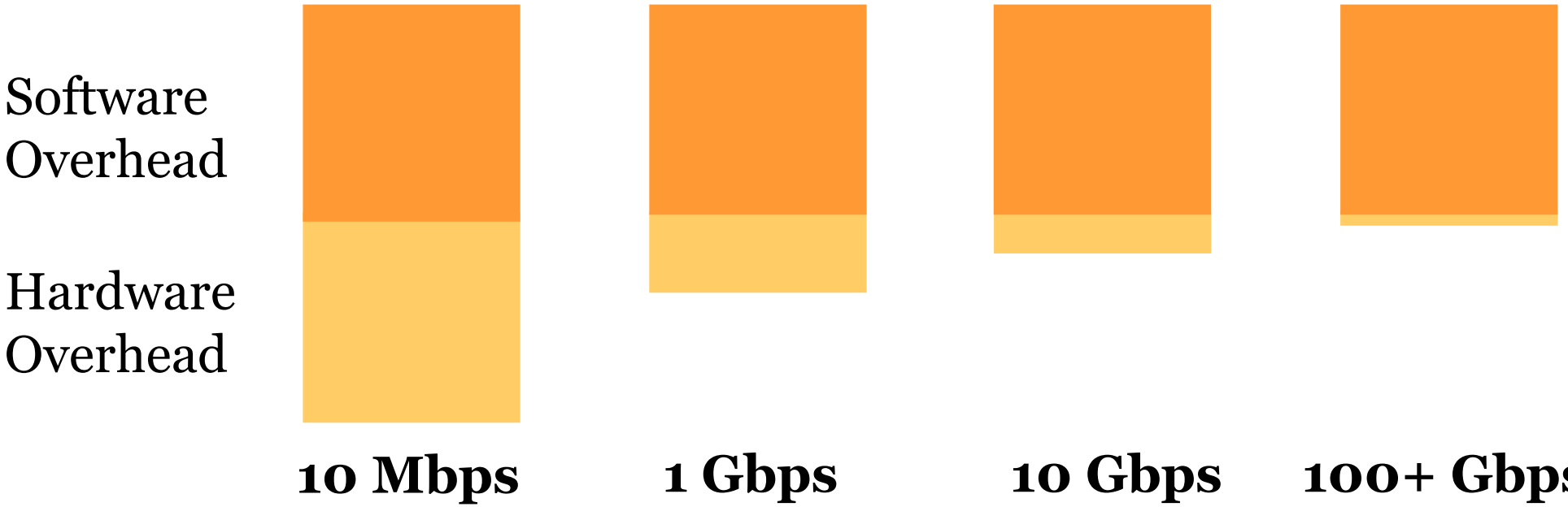
- GPU
  - Large thread parallelism
  - SIMD computation
  - Limited on-chip memory
  - Large global memory w/ increasing bandwidth
- FPGA
  - A set of programmable logic blocks
  - Logic blocks can be configured to perform complex functions
  - On-chip memory configurable
- ASIC
  - Once you know what you are doing





Networking Capabilities

- Bandwidth is increasing considerably
- Transmission speeds have improved (optical networking, etc)
- Messaging overhead is *still* an issue



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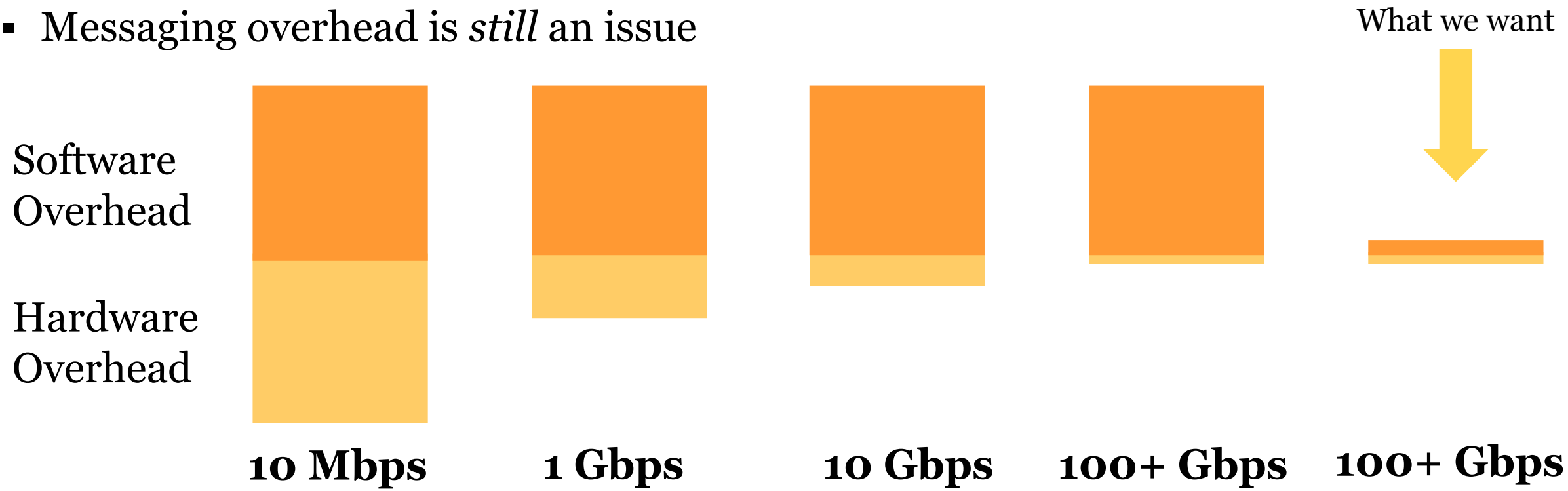
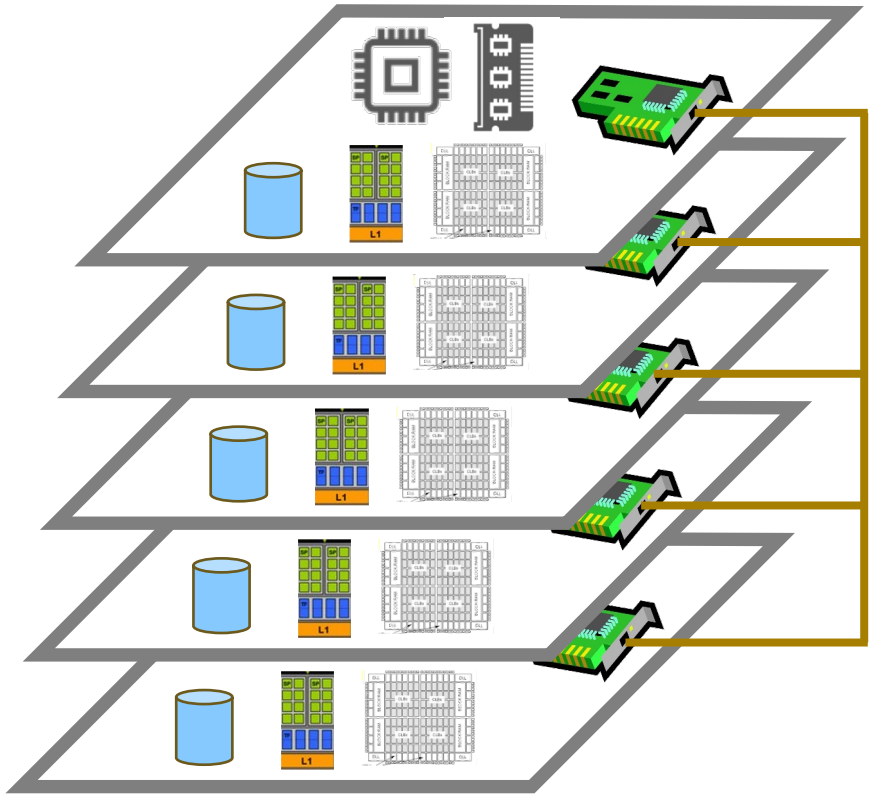


CURRENT ENVIRONMENT

Current Data Centre Rack and Blade Design



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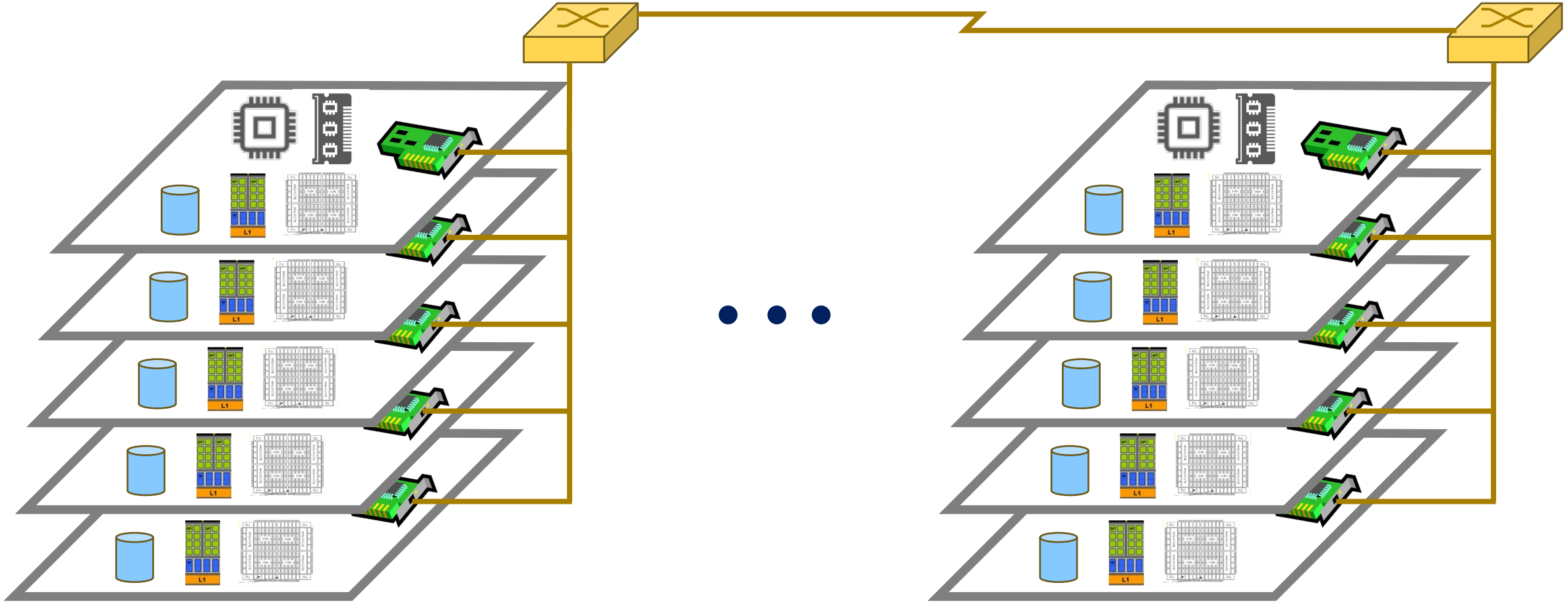
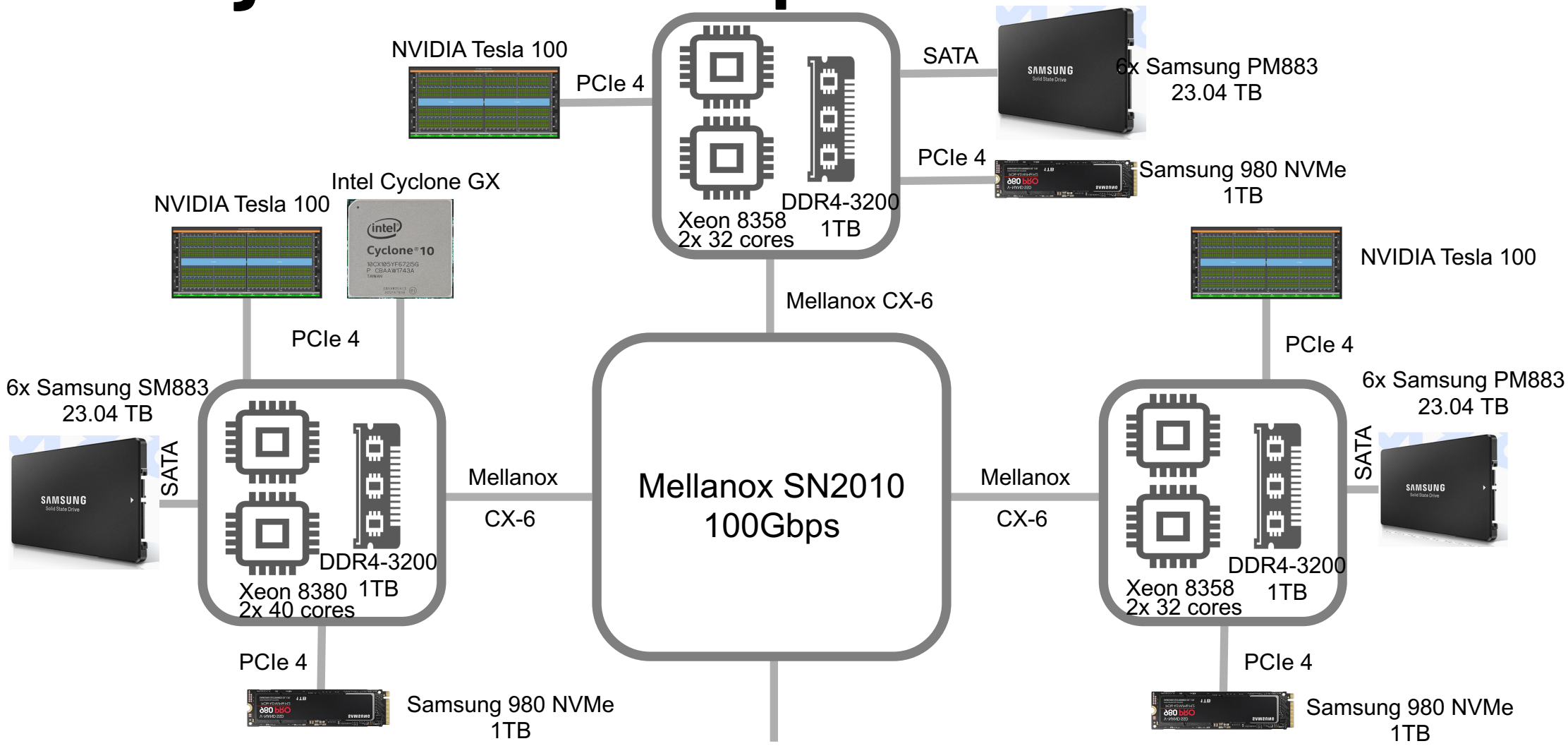


Our Existing Platform as Example



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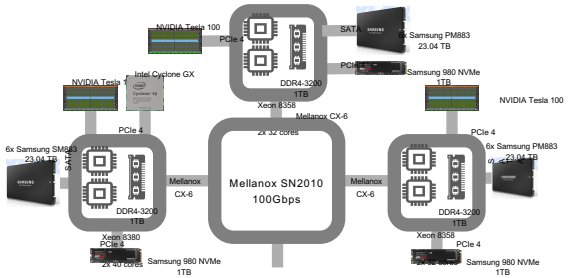

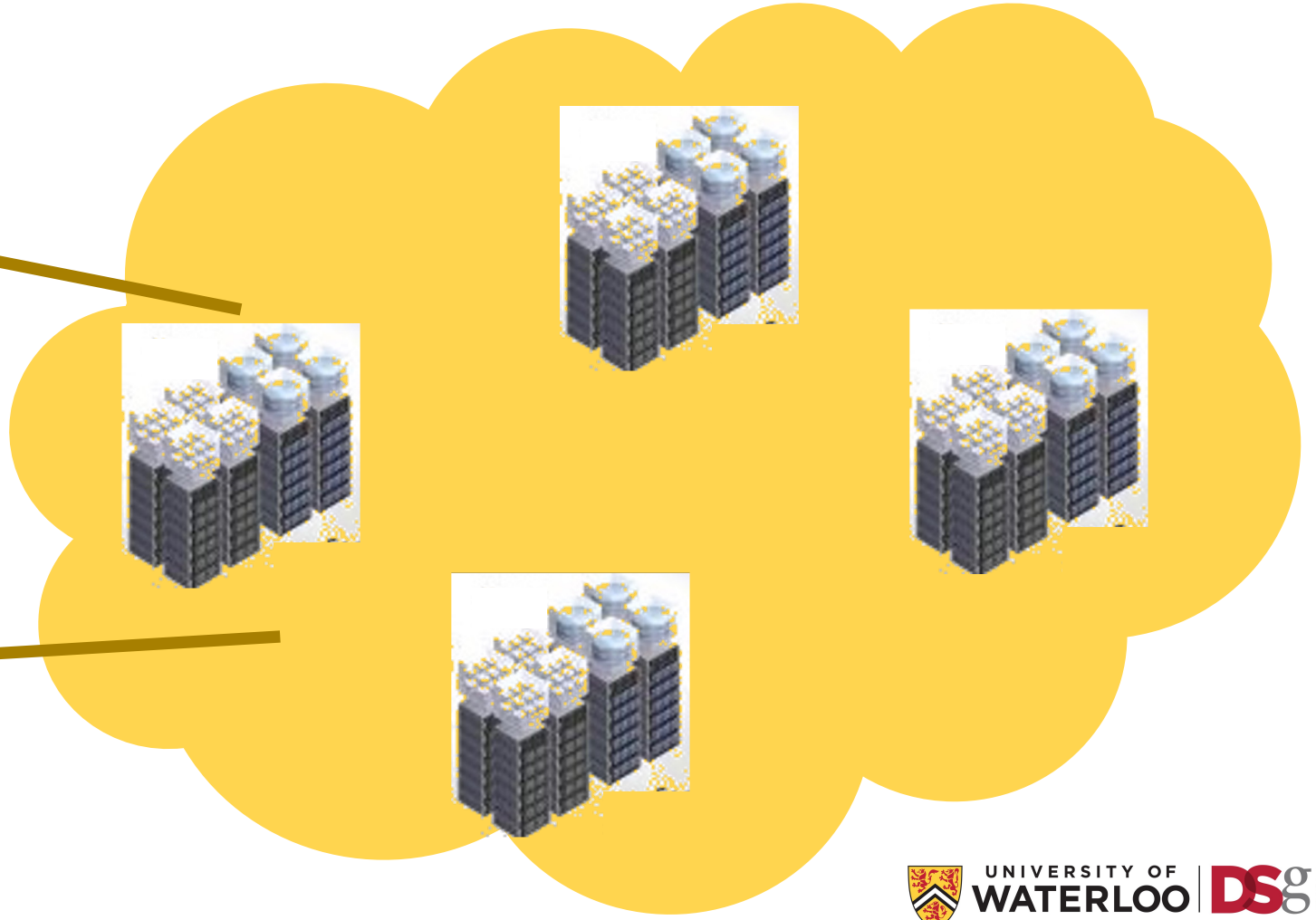

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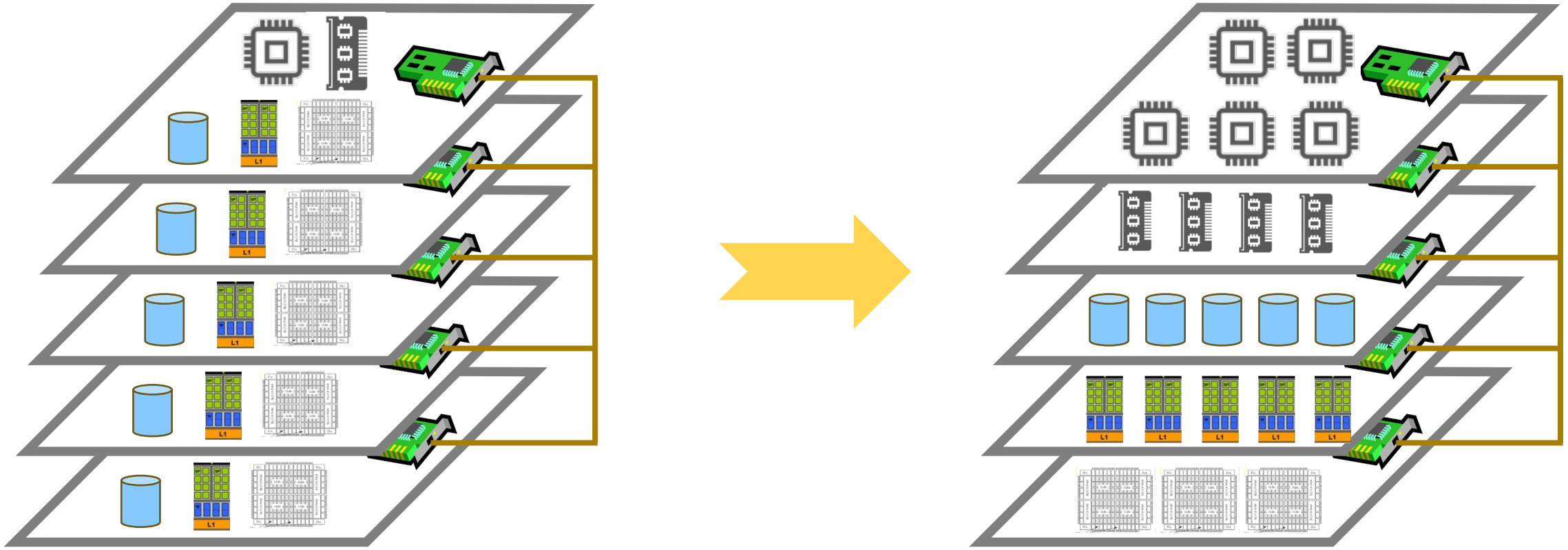
Disaggregation

Disaggregated Rack and Blade Design



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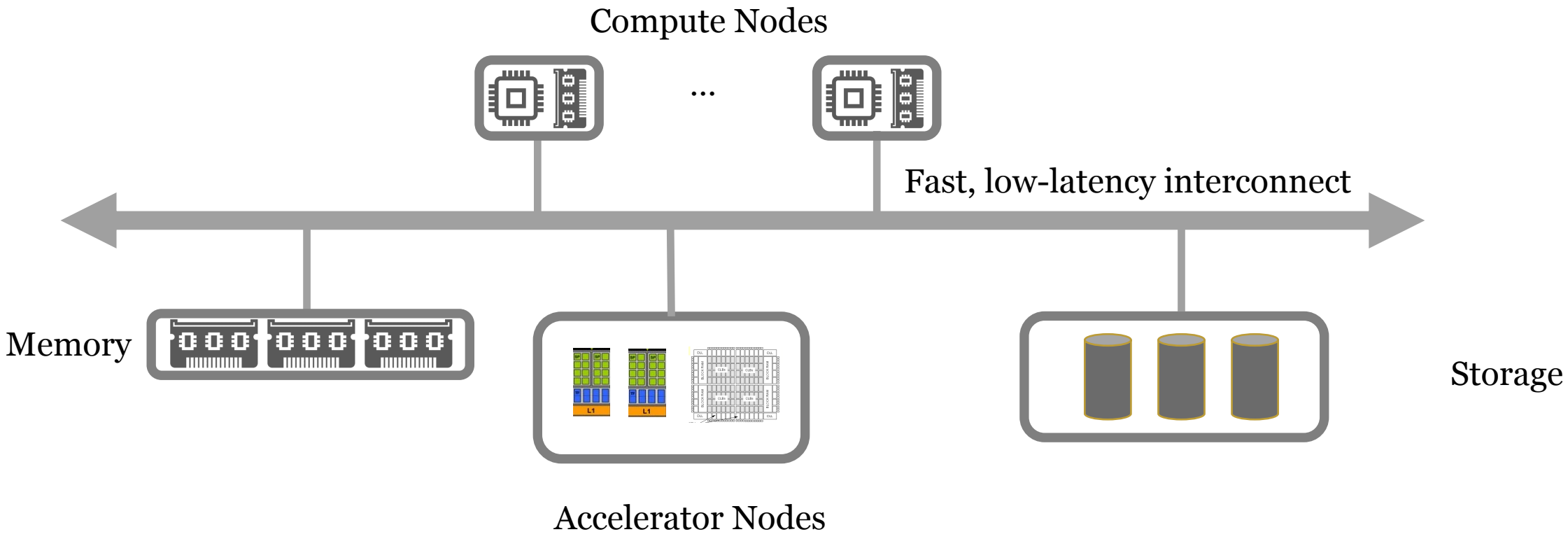

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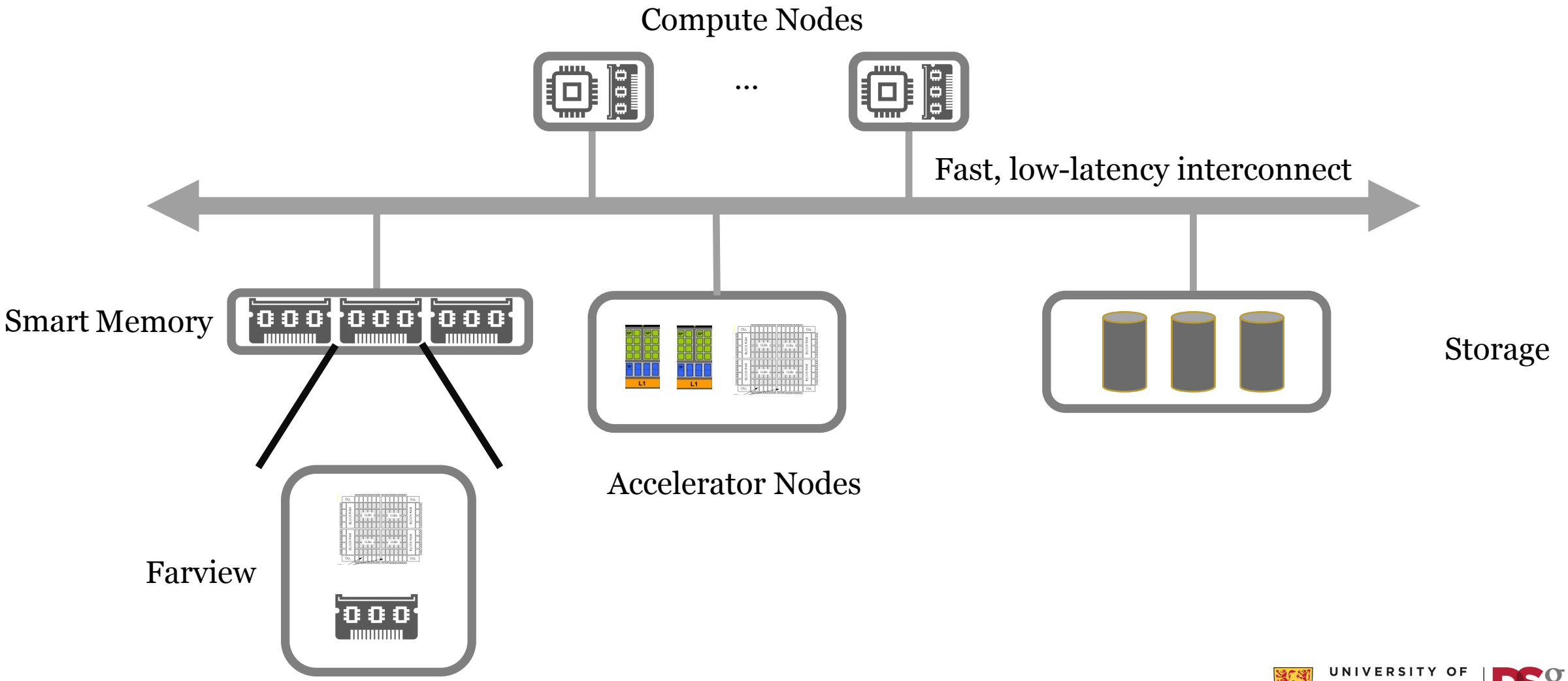

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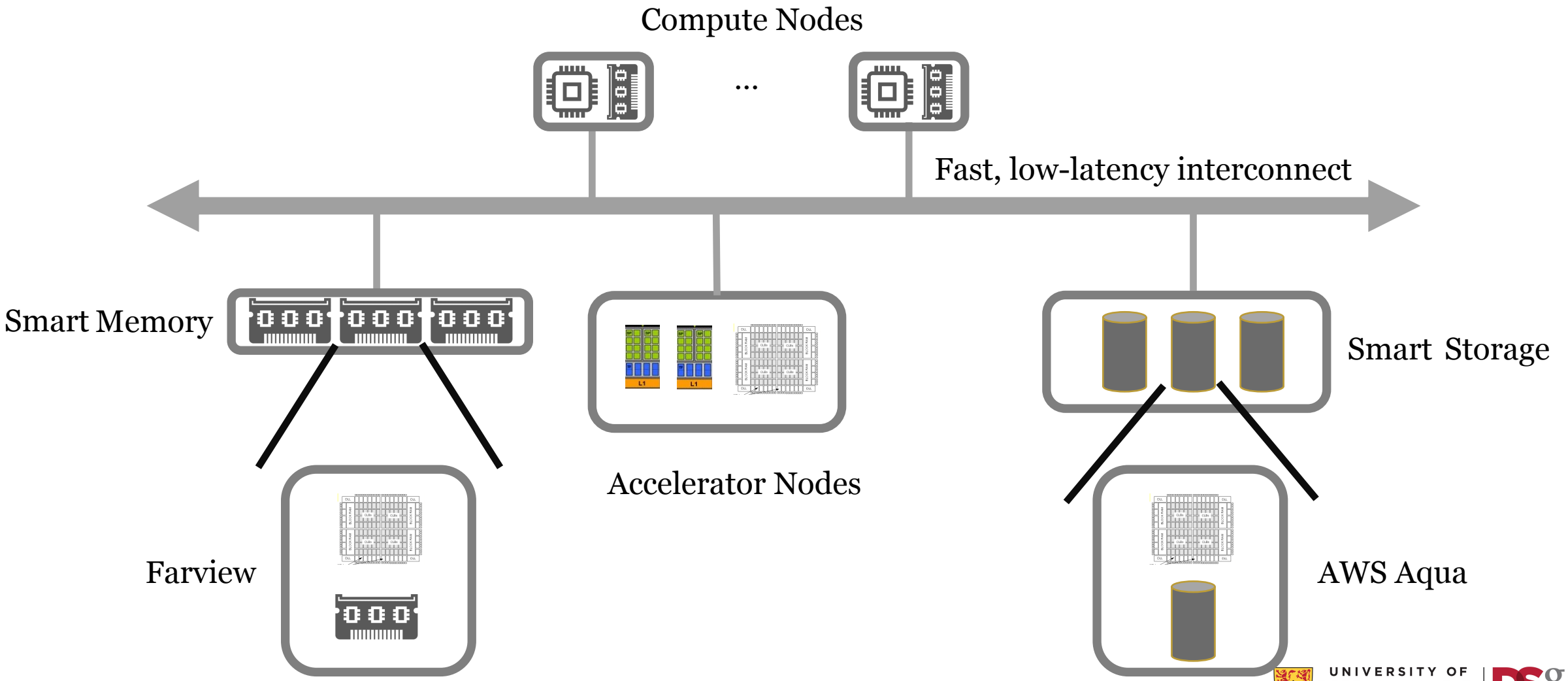

What Are We Disaggregating?

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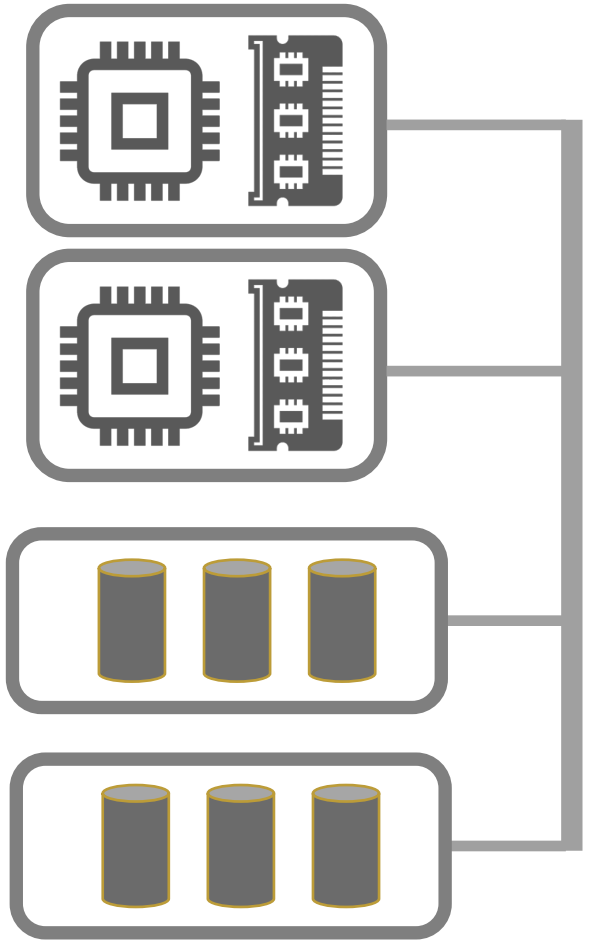
- Storage



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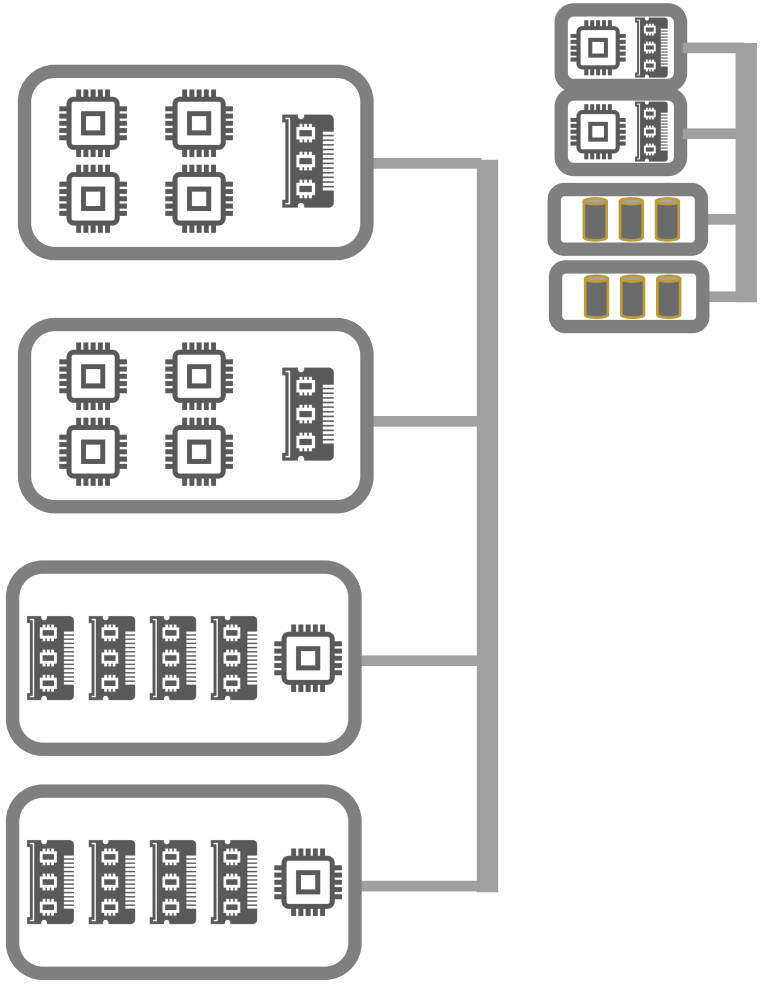

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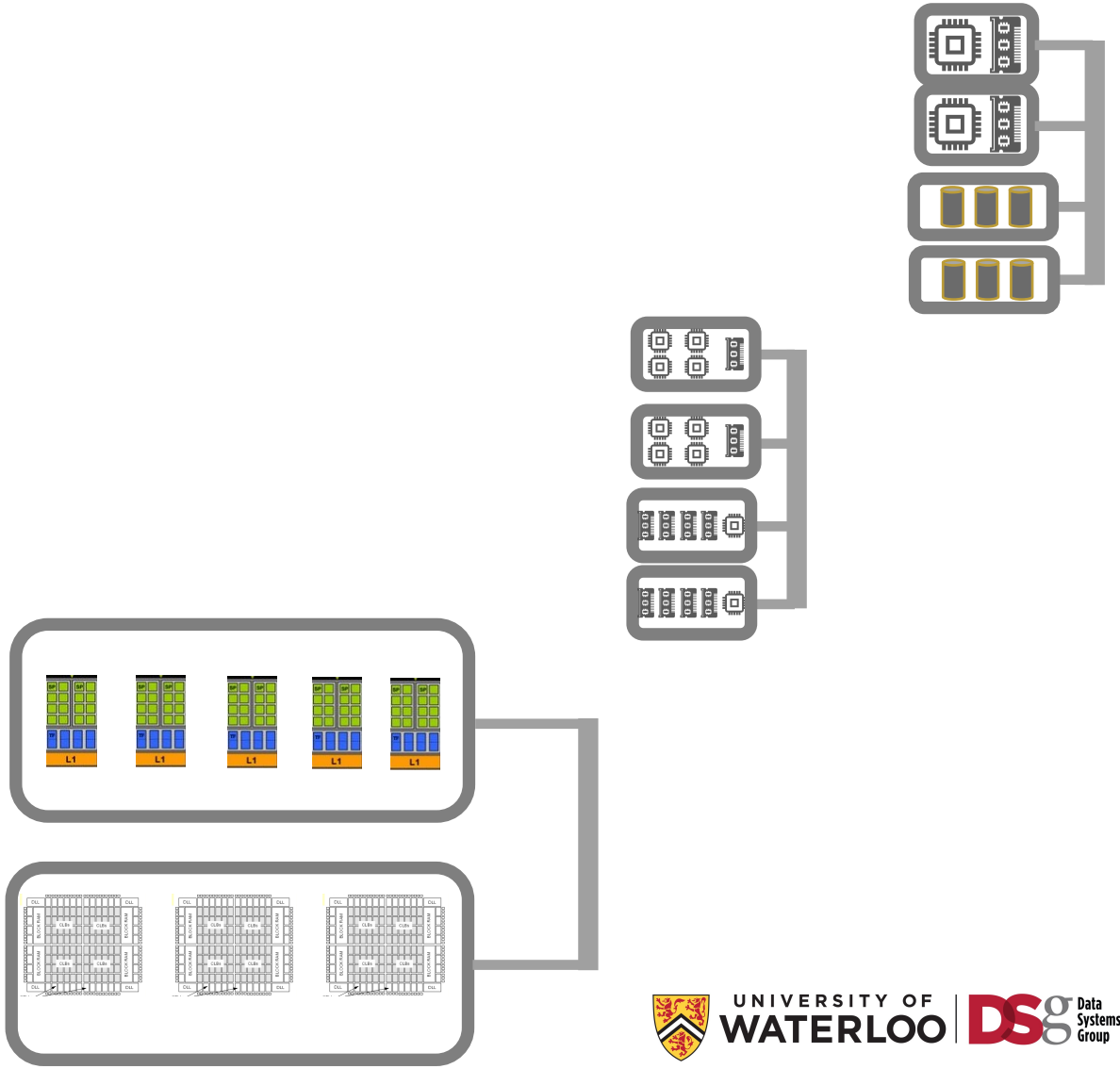

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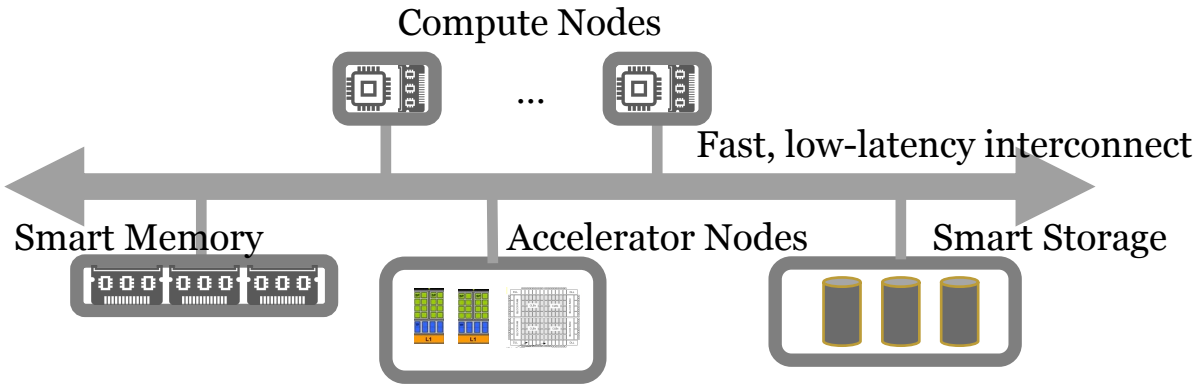
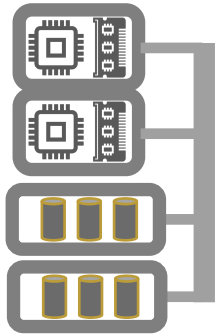
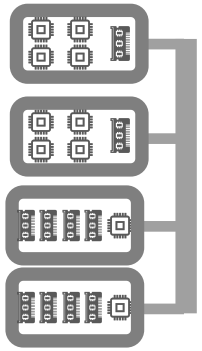
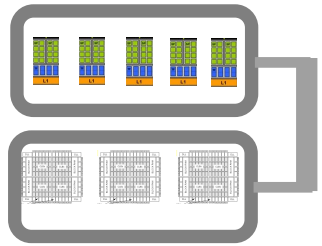


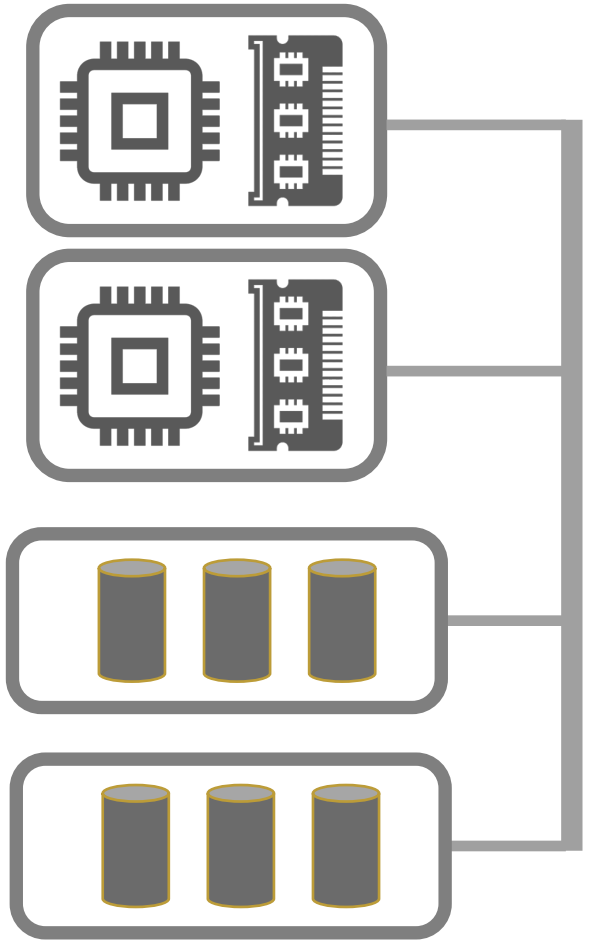






Storage Disaggregation

- Cloud deployments prefer shared disk[1]
  - Easier for crash recovery; no need for migration
- Easier for serverless computing
  - Faster startup, easier shutdown
- Independent and easy scaling of storage
- TCP/IP for connection may be sufficient



[1] J. Tan et al. Choosing a Cloud DBMS: Architectures and Tradeoffs, *Proc. VLDB*, 2019.

Storage Disaggregation is Well Understood

OLTP Systems

- Amazon Aurora[1]
- Microsoft Socrates[2]
- Google AlloyDB[3]
- Alibaba PolarDB[4]

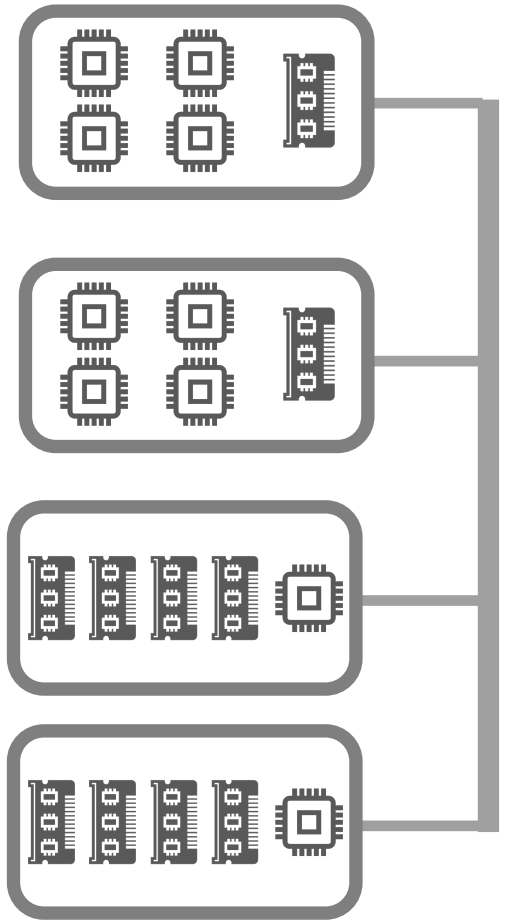
OLAP Systems

- Snowflake[5]
- Amazon Redshift[6]

[1] A. Verbitsky et al. Amazon Aurora: Design Considerations for High Throughput Cloud-Native Relational Databases, *Proc. SIGMOD*, 2017.
[2] P. Antonopoulos et al. Socrates: The New SQL Server in the Cloud, *Proc. SIGMOD*, 2019.
[3] https://cloud.google.com/blog/products/databases/alloydb-for-postgresql-intelligent-scalable-storage
[4] F. Li. Cloud-Native Database Systems at Alibaba: Opportunities and Challenges, *Proc. VLDB Endow.*, 2019.
[5] B. Dageville et al. The Snowflake Elastic Data Warehouse, *Proc. SIGMOD*, 2016.
[6] N. Armenatzoglou et al. Amazon Redshift Re-invented, *Proc. SIGMOD*, 2022.

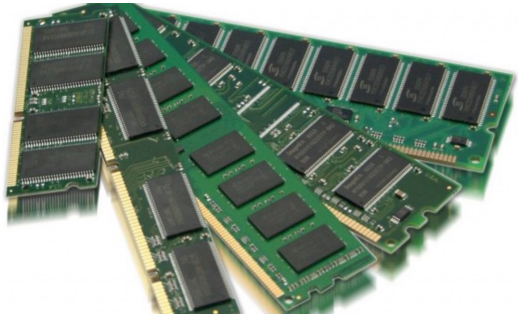
Memory Disaggregation

- Newer direction



Memory Disaggregation

- Newer direction
- The case for memory disaggregation
  - DRAM is an expensive resource in the cloud – 50% of server cost on Azure[1]



Azure

[1] H. Li et al. Pond: CXL-Based Memory Pooling Systems for Cloud Platforms, arXiv 2203.00241, 2022.

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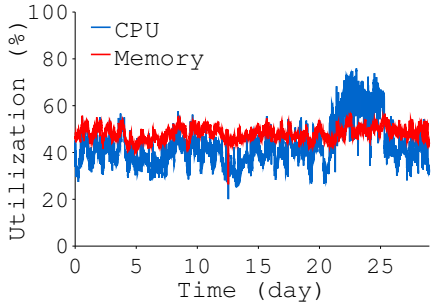
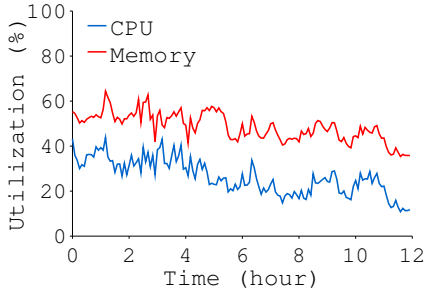


Google Cluster



Alibaba Cluster

[1] H. Li et al. Pond: CXL-Based Memory Pooling Systems for Cloud Platforms, arXiv 2203.00241, 2022.

[2] Y. Shen et al. Pond: LegoOS: A Disseminated, Distributed OS for Hardware Resource Disaggregation, *Proc. OSDI*, 2018.

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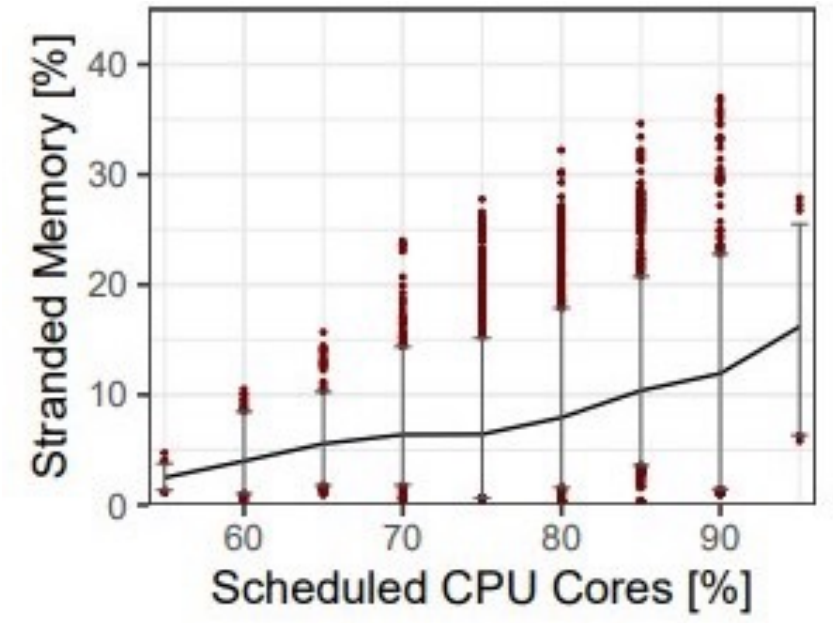

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[3] https://www.nextplatform.com/2022/07/11/microsoft-azure-blazes-the-disaggregated-memory-trail-with-znuma/

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  - Independent and elastic scaling of compute and memory[4]

AWS EC2 Instance	vCPU	DRAM (GB)
r6g.medium	1	8
r6g.large	2	16
r6g.xlarge	4	32
r6g.2xlarge	8	64
r6g.4xlarge	16	128
r6g.8xlarge	32	256
r6g.16xlarge	64	512

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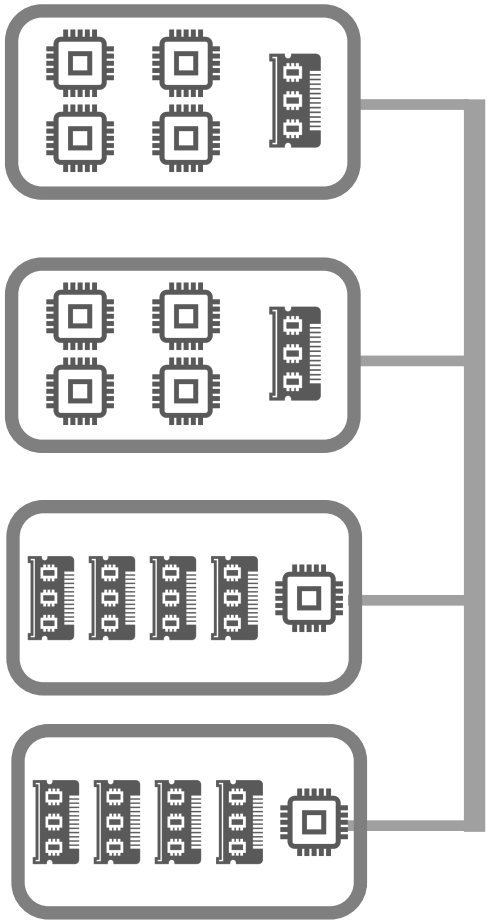
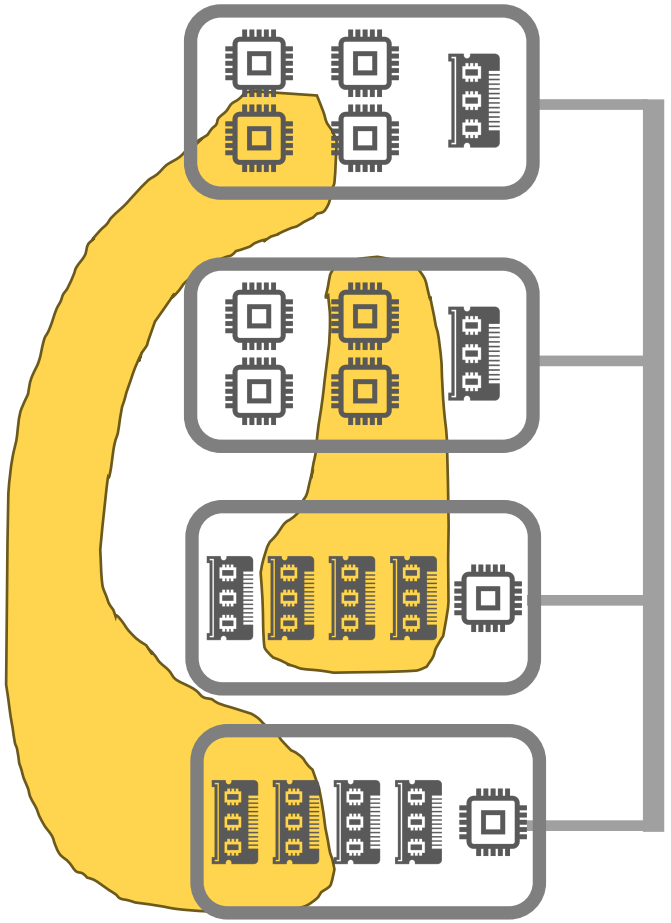
[4] https://aws.amazon.com/ec2/instance-types/

The Case for Memory Disaggregation



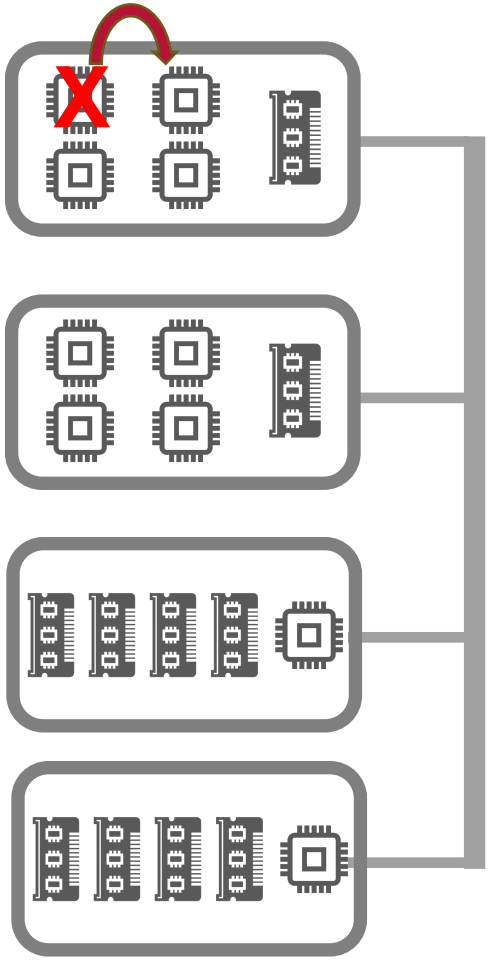
The Case for Memory Disaggregation

- Flexibility in VM configuration
  - Independent allocation



The Case for Memory Disaggregation

- Flexibility in VM configuration
  - Independent allocation
- Fault tolerance
  - Independent failure

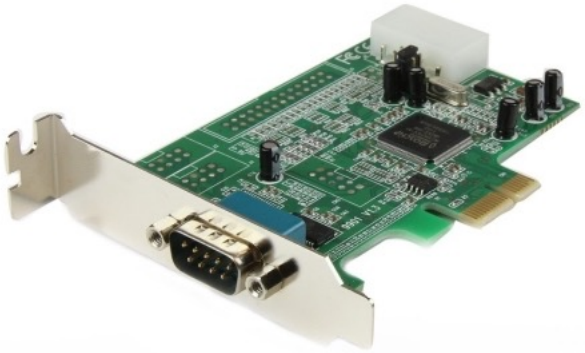


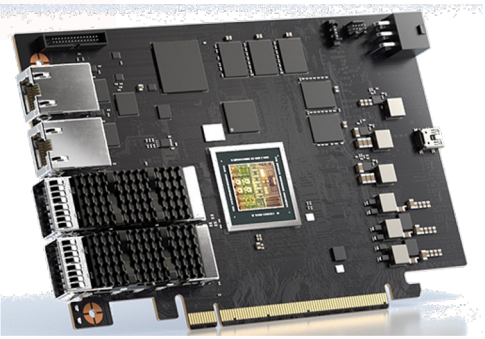
Critical Component in Disaggregation (Beyond Storage)

Low latency, high bandwidth interconnect

Networking Hardware Improvements

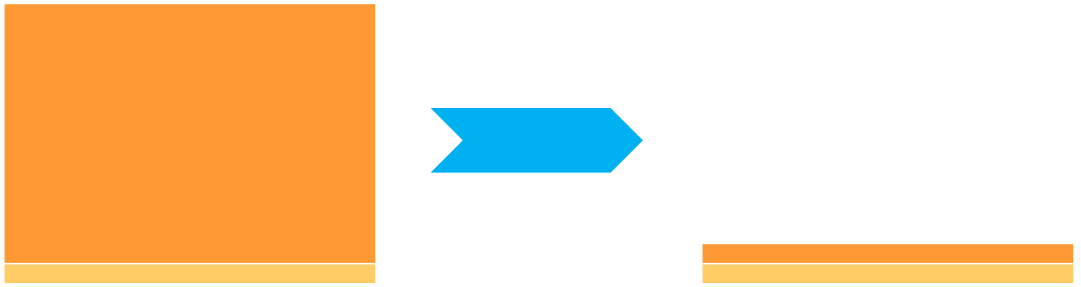
- Basic/Foundational NIC
  - Simple network connection
  - Usually 1Gbps – 25Gbps
  - Relies on CPU for protocol processing – ≥ 30% server CPU for higher speeds
- Smart NIC
  - Offload network protocol processing
  - Have their own processor, memory & OS
  - ≥ 50Gbps
- DPU
  - Smart NIC + security + storage + …
  - Custom chips and/or FPGAs





T. Döring et al., SmartNICs: Current Trends in Research and Industry, 2020
https://www.net.in.tum.de/fileadmin/TUM/NET/NET-2021-05-1/NET-2021-05-1_05.pdf

Networking Software Improvements



100+ Gbps

Networking Software Improvements

- High overhead of TCP

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- High overhead of TCP
  - "Data center tax"[1]

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John Ousterhout
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  - RDMA (Infiniband, RoCE)
  - CXL

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  - RDMA (Infiniband, RoCE)
  - CXL
- Efficient RPC protocol – higher level

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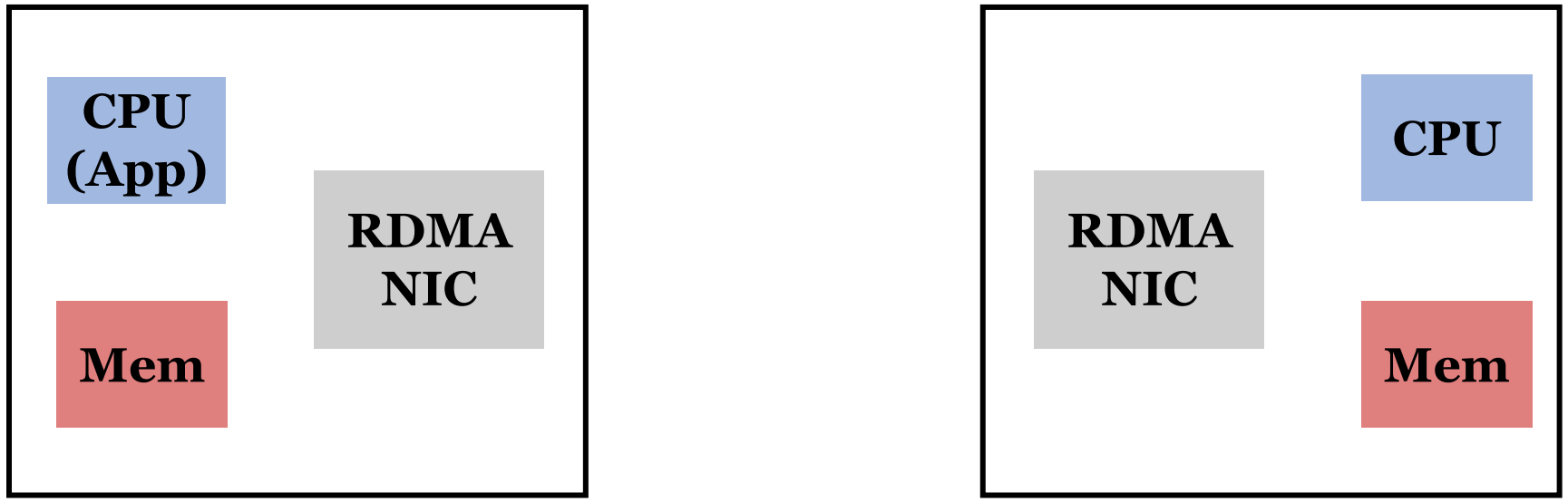
RDMA – Remote Direct Memory Access

Physical View



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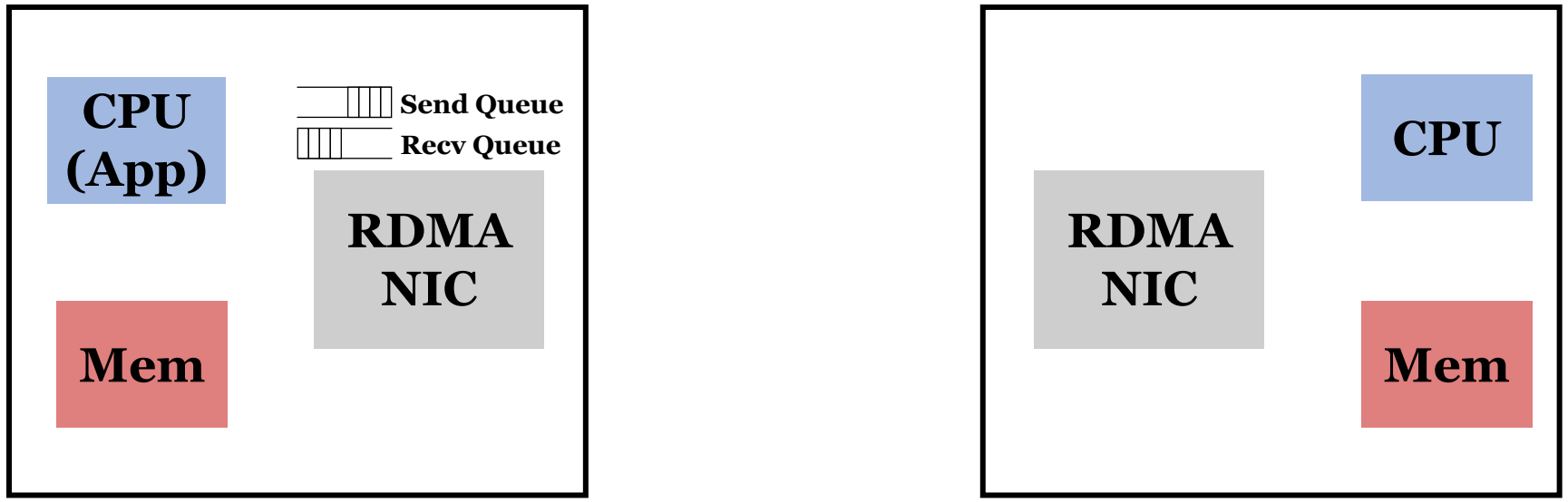

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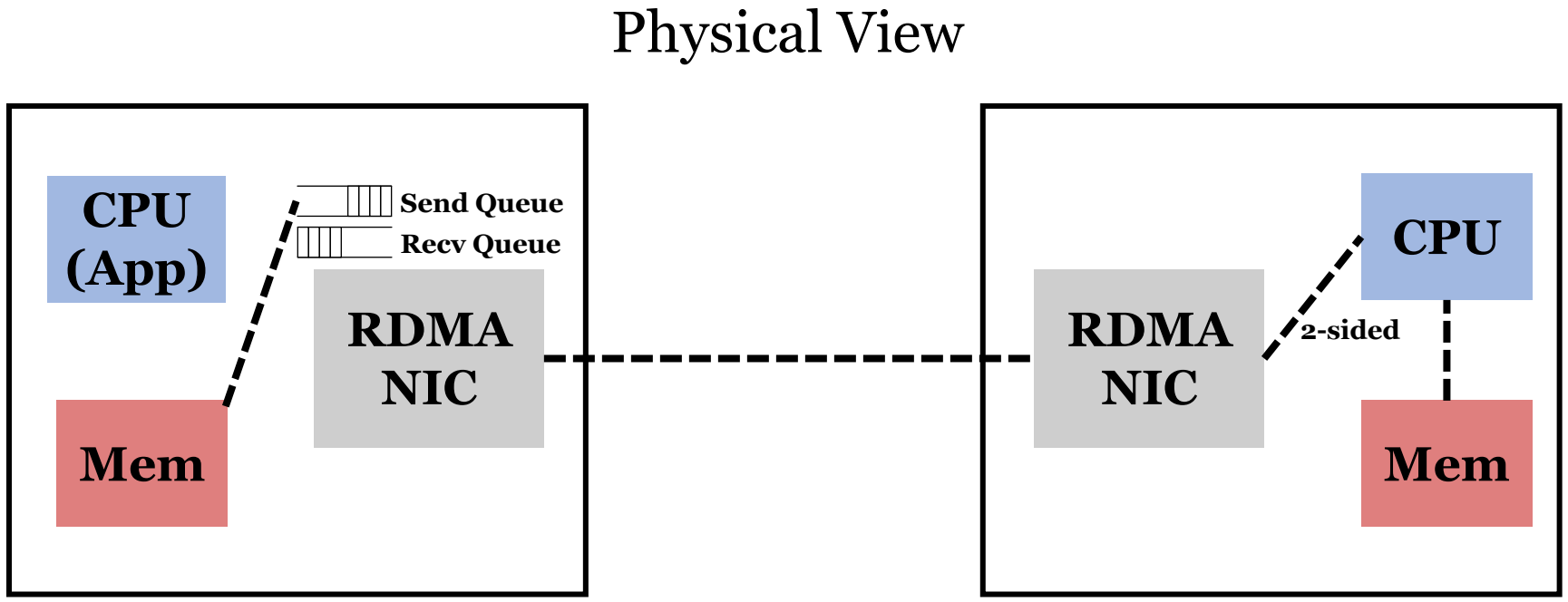

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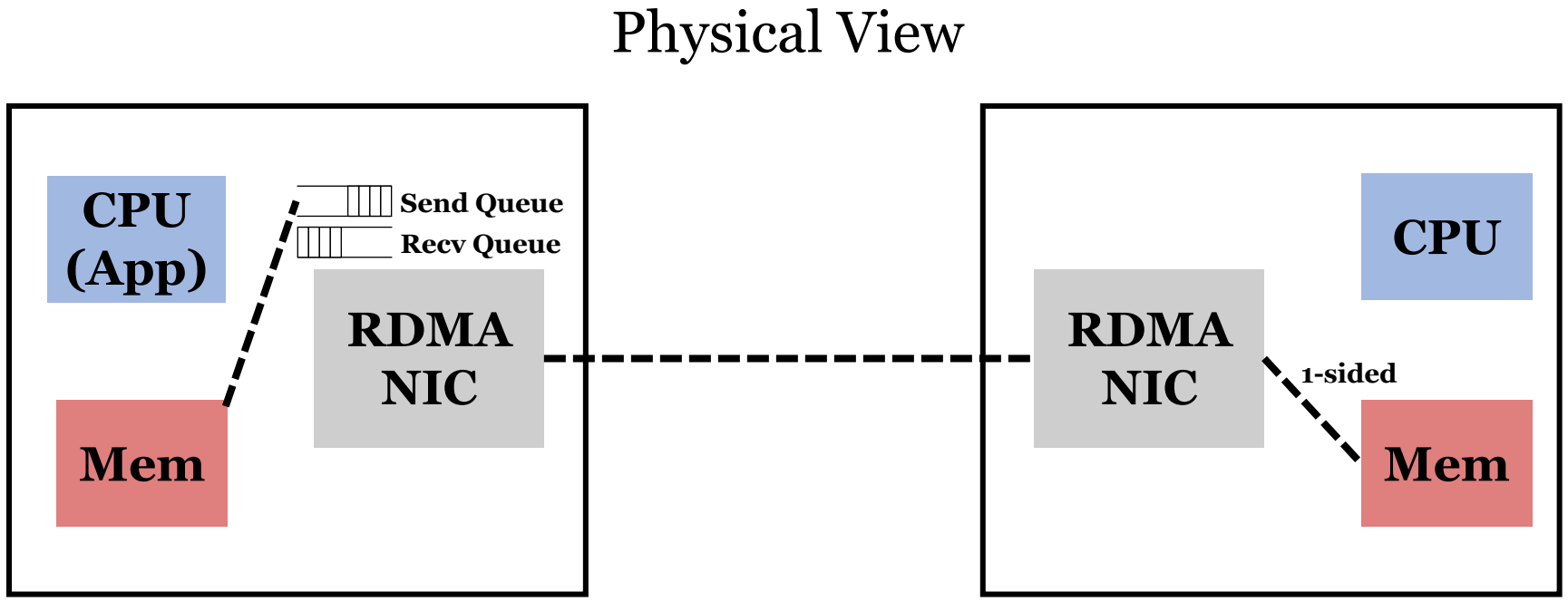

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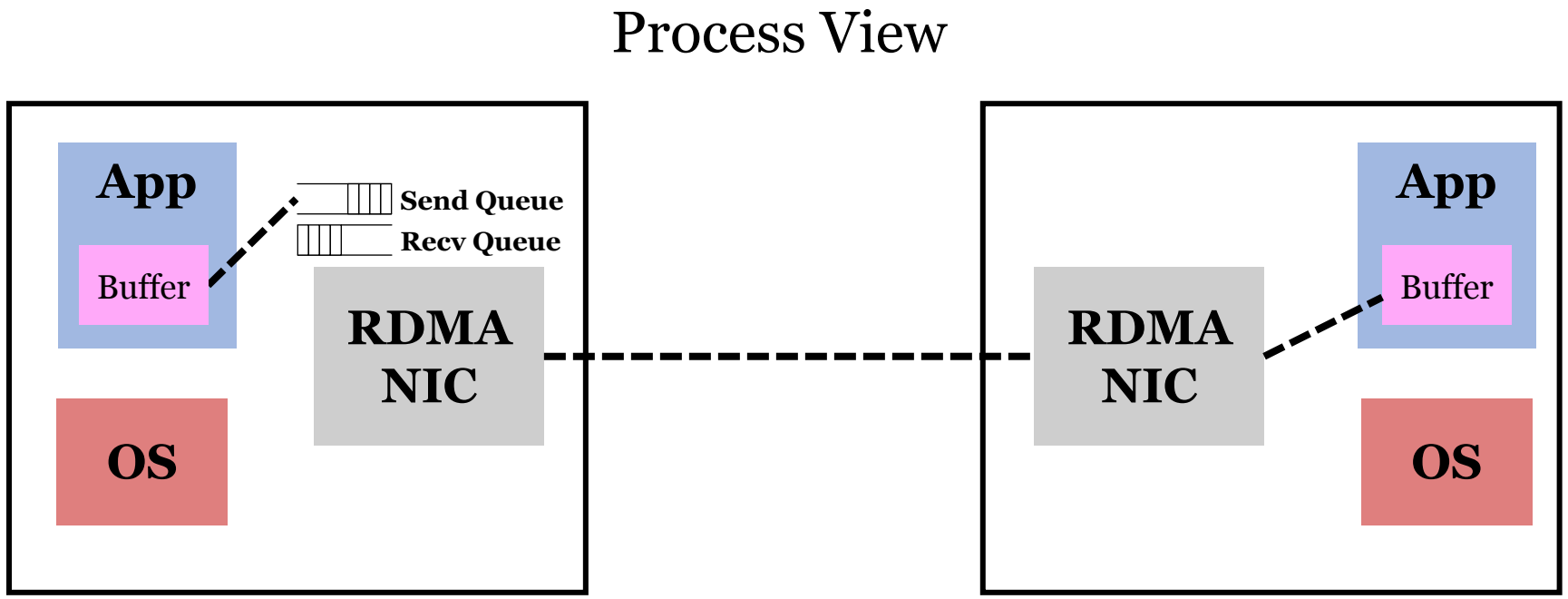

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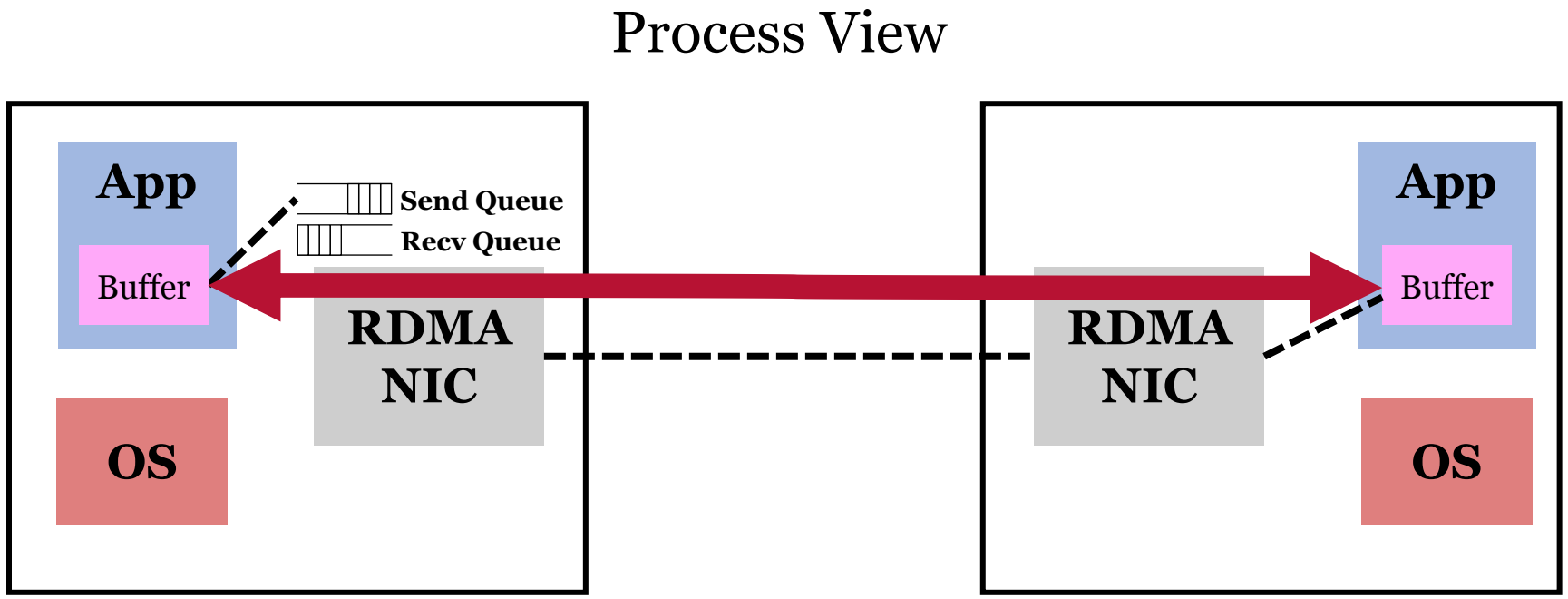

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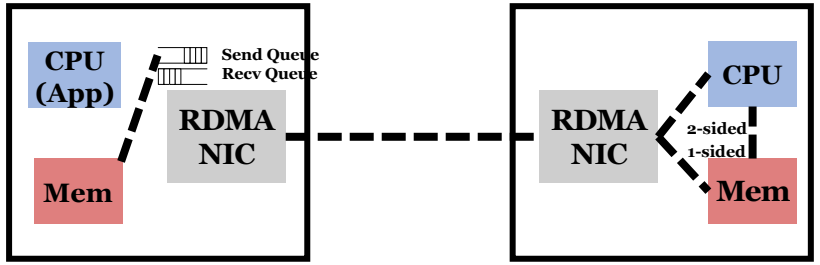
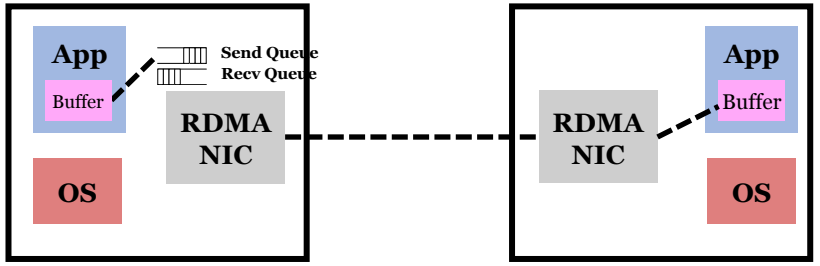


Process View



- Zero-copy networking
- OS bypass
- CPU bypass
- Message-based communication

CXL – Compute Express Link

- High bandwidth, low latency, cache coherent interconnect
- Avoids memory copy between application memory and NIC buffers
- Does not require a CPU (or controller) on memory nodes

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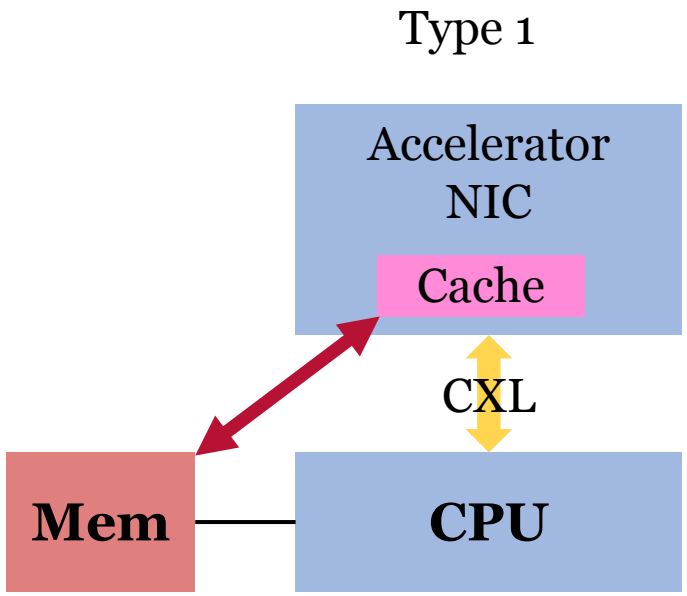

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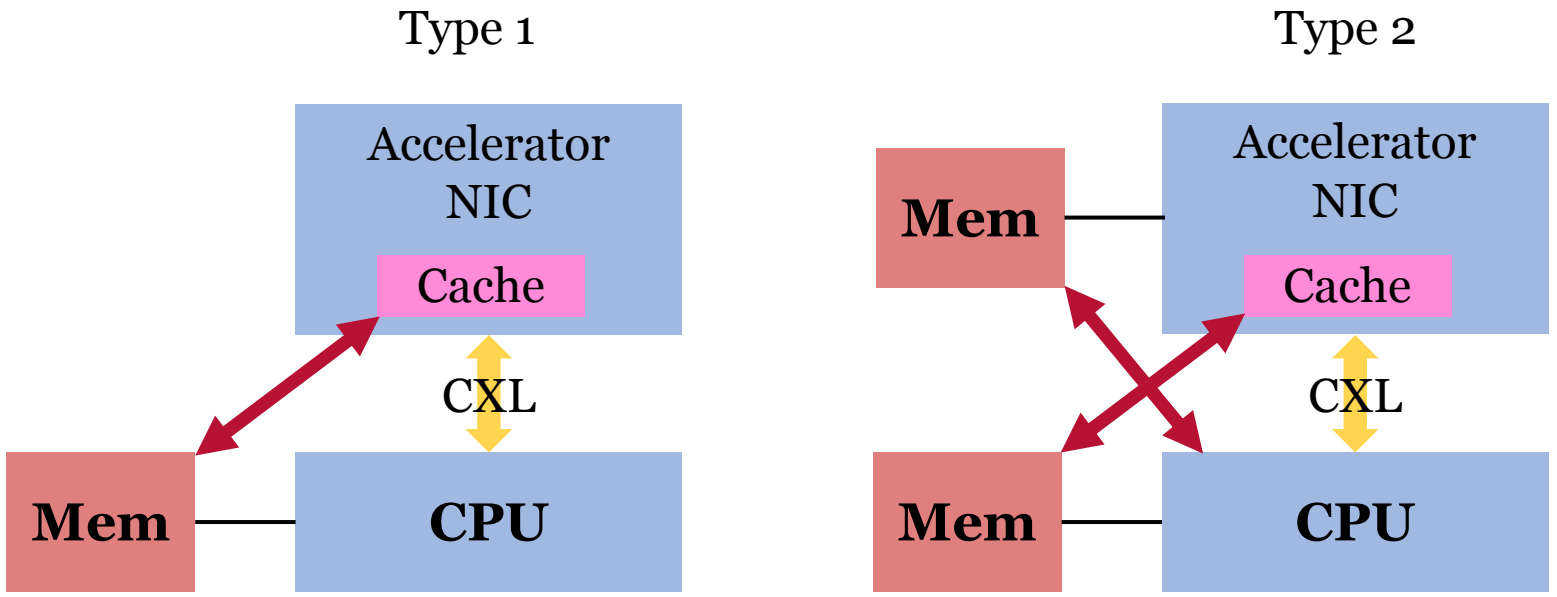

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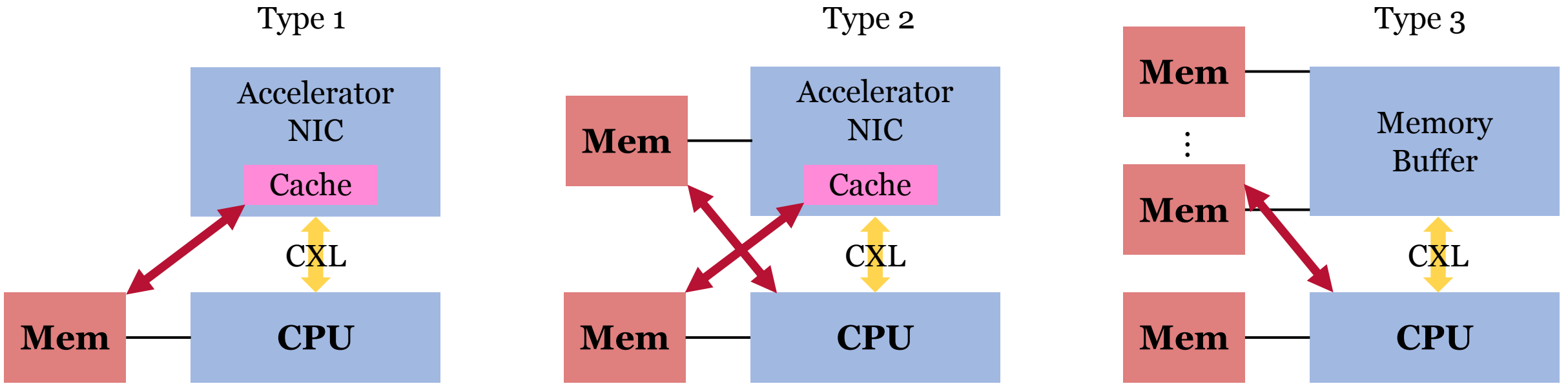

CXL vs RDMA

RDMA

- Copies data from application memory to NIC buffers
- Copies data across the network
- Requires handling of cache coherence (in some configurations)
- Requires a CPU/controller at memory nodes

CXL

- Does not copy data into NIC buffers
- Does not copy data across the network, accesses remote memory
- Provides a hardware supported coherent cache
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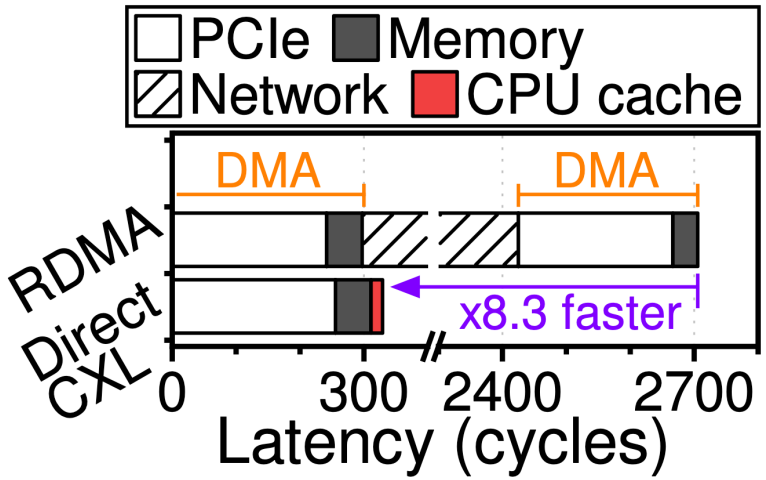
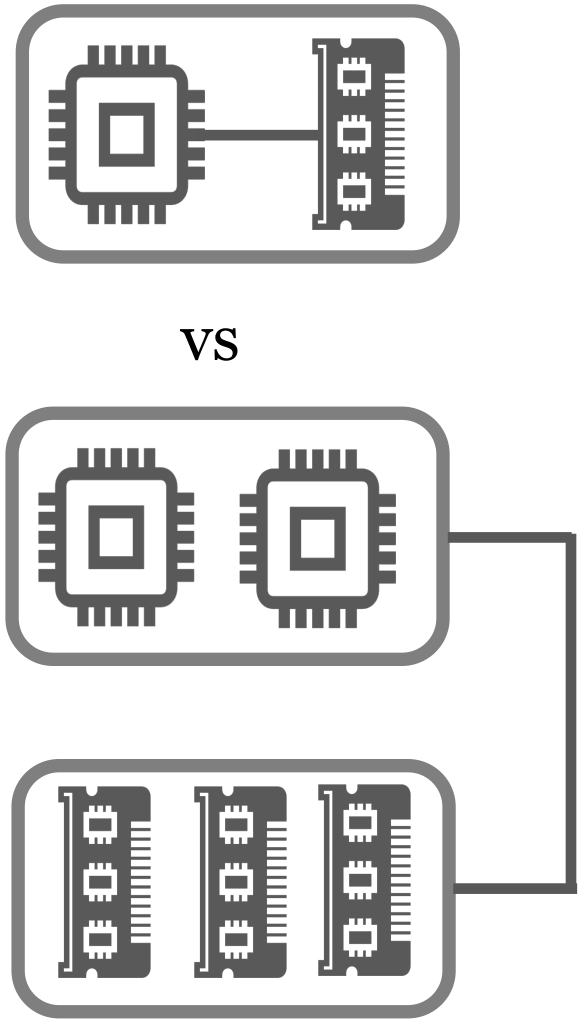


[1] D. Gouk, et al. Direct Access, High Performance Memory Disaggregation with DirectCXL. *Proc. USENIX ATC*, 2022.

Main Issue with Memory Disaggregation

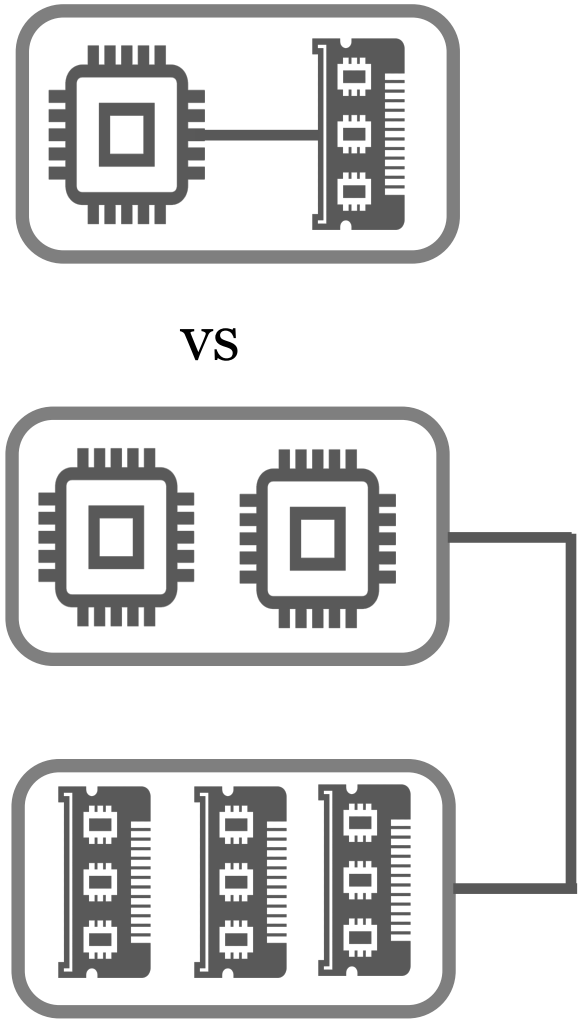
Access Latency



Main Issue with Memory Disaggregation

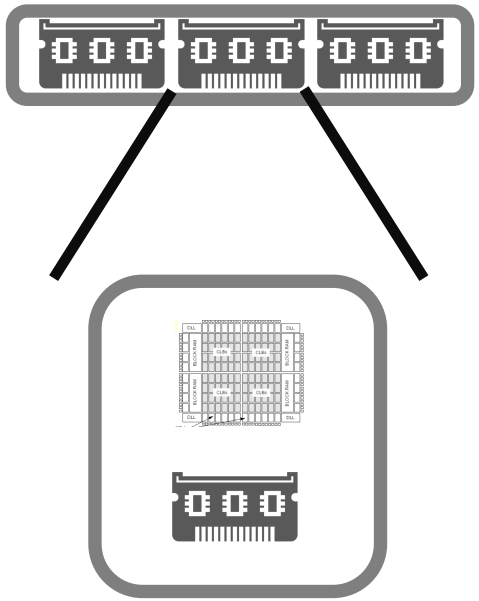
Access Latency

Near-data Processing
+
Optimized Design



Near-Data Processing: The Case for Smart Memory

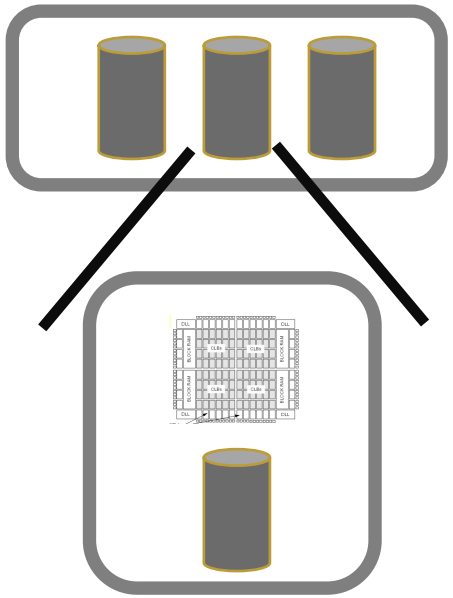
- Minimize data movement from memory to CPU
- Also
  - DRAM growing but not at the same speed as the demand
  - The independent provisioning issue again
- Farview: buffer pool on disaggregated memory
  - Push down operators to memory → reduce data movement
  - Centralize buffer cache on disaggregated memory → reduce memory requirement on compute nodes



D. Korolija et al. Farview: Disaggregated Memory with Operator Off-loading for Database Engines, *Proc. CIDR*, 2002

Near-Data Processing: The Case for Smart Storage

- Further restrict data movement
  - Pushing near-data computation to the storage
- Similar to old idea of database machines



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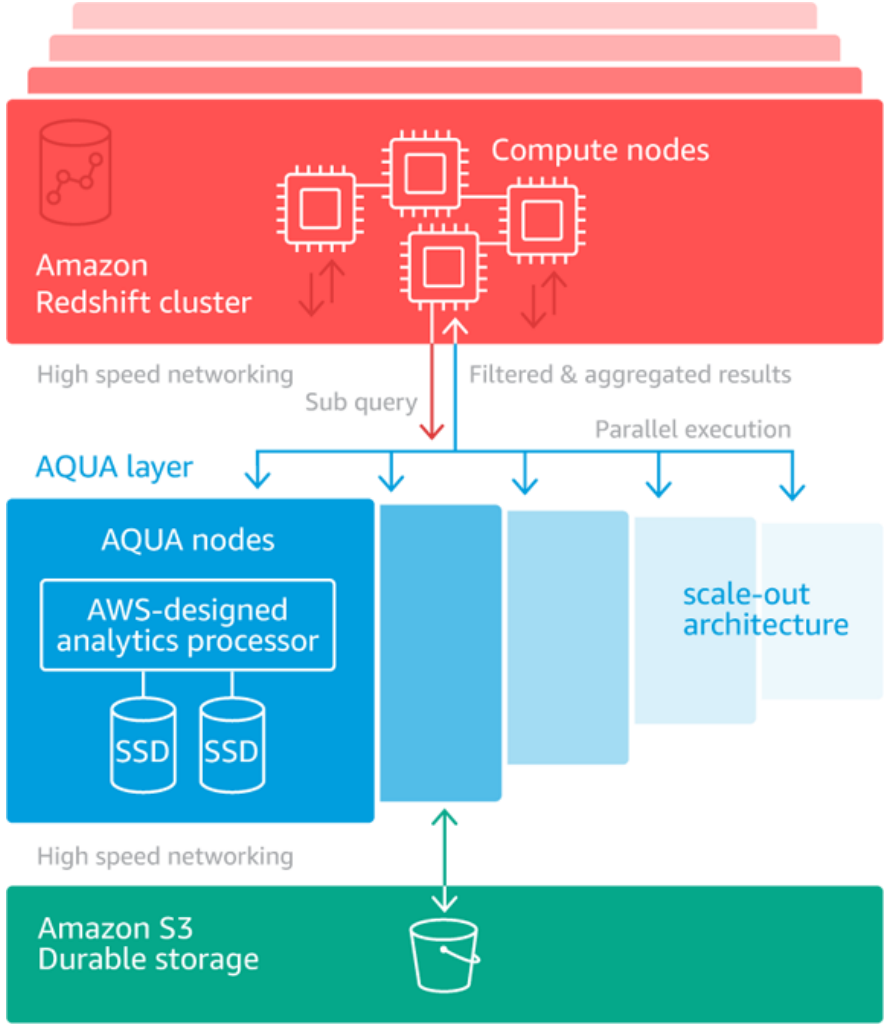
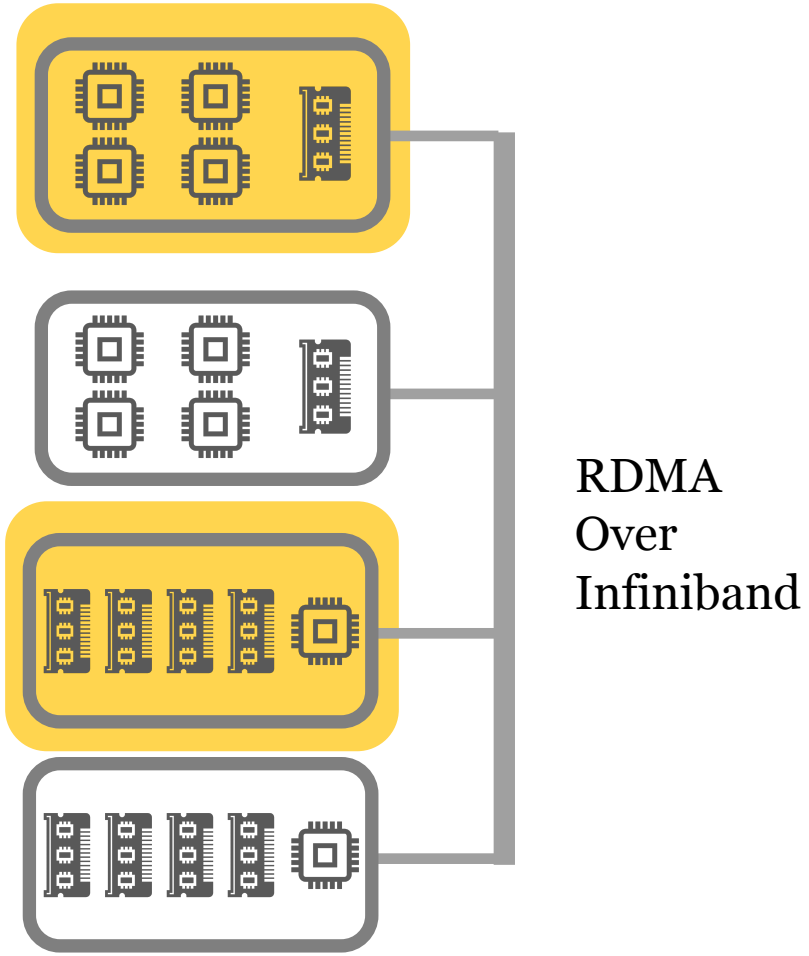
- AWS Aqua nodes



J.Barr. AQUA (Advanced Query Accelerator) – A Speed Boost for Your Amazon Redshift Queries, 2021
https://aws.amazon.com/blogs/aws/new-aqua-advanced-query-accelerator-for-amazon-redshift/

Our Work

- Scope: in-memory DBMS
- Compute nodes
  - Strong computing, but limited local memory
  - SQL parser, optimization, transaction, buffer
  - Each compute can read/write
- Memory nodes
  - Form a DSM layer accessed by all compute nodes



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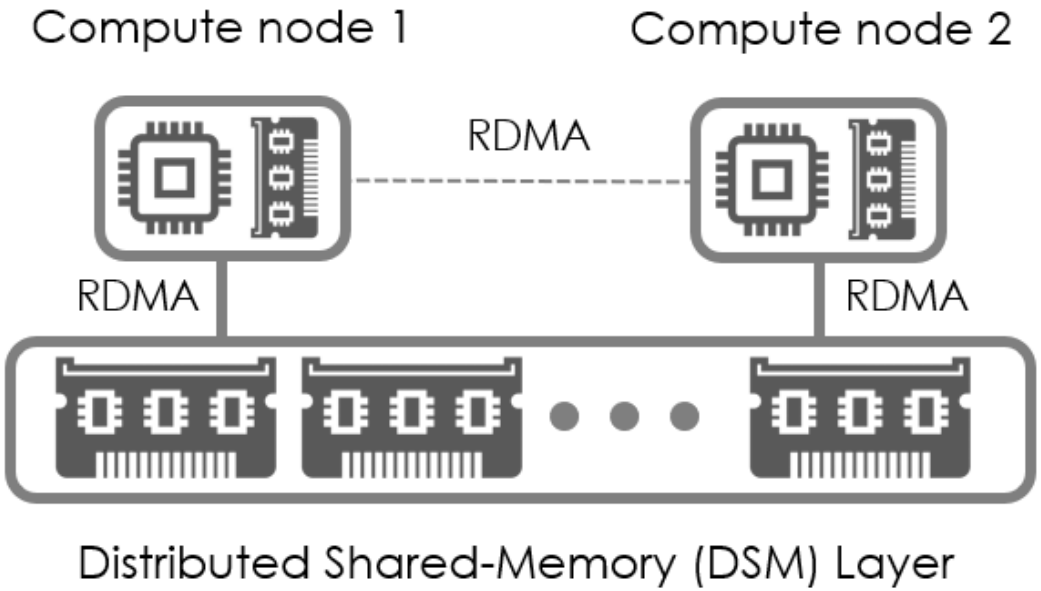
Transaction Execution Design



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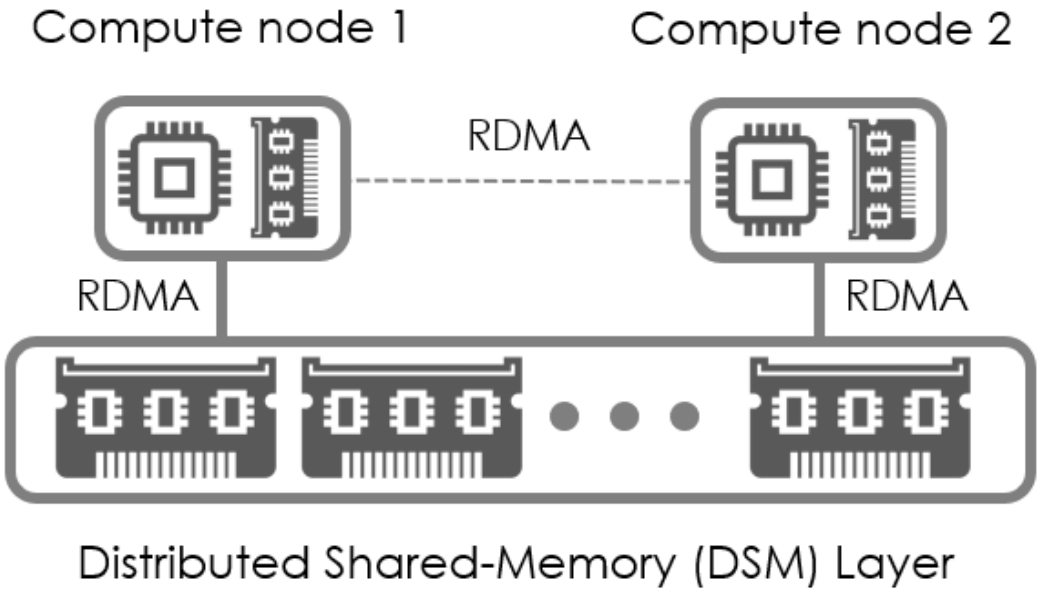

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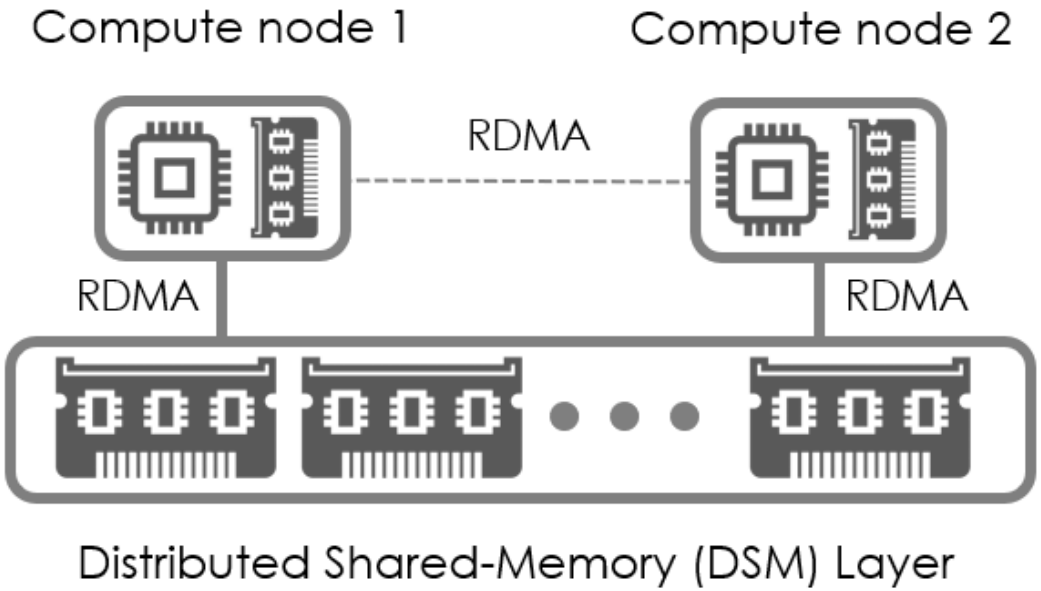

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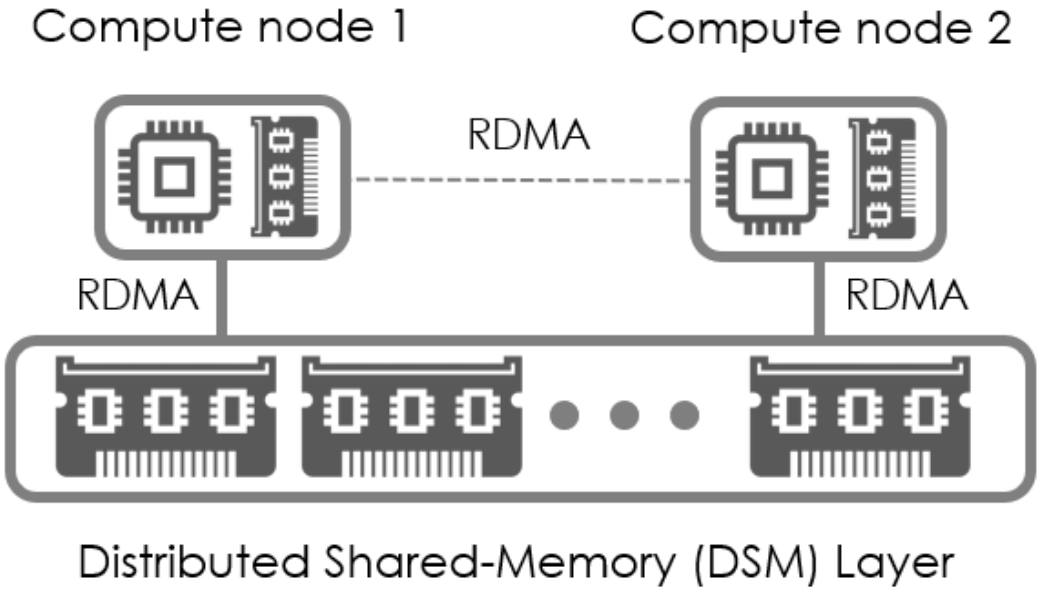
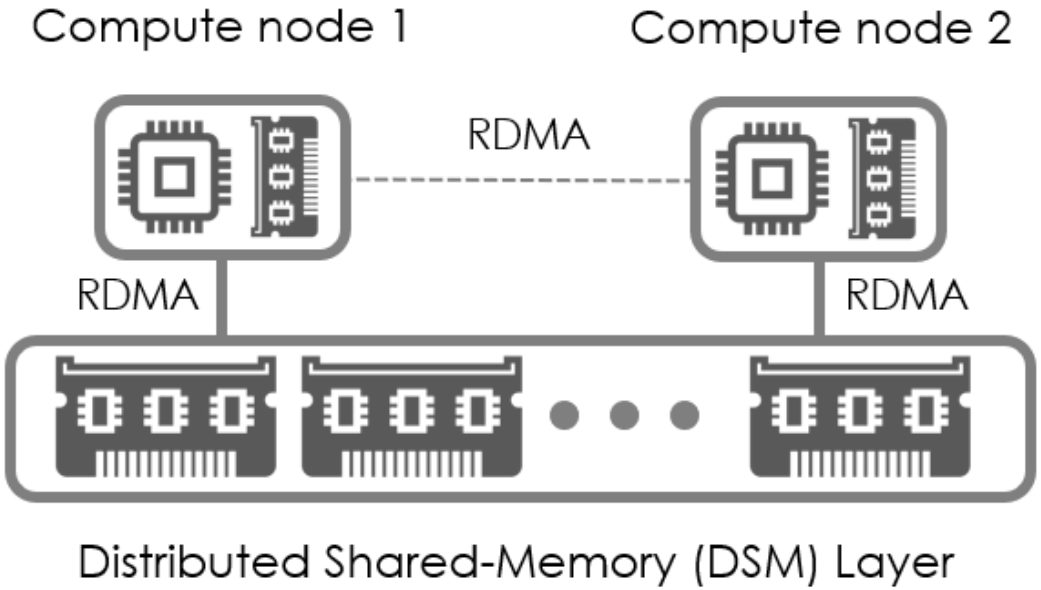
- Challenge: Distributed commit
  - Depends on the model
- Challenge: Concurrency Control Algs
  - Cannot directly use existing CC protocols, e.g., 2PL, MVCC, OCC



R. Wang et al. The Case for Distributed Shared Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

Transaction Execution Design

- Challenge: Cache coherence
  - This is not an issue if CXL is used
  - RDMA: No hardware-supported cache coherence between compute nodes
- Challenge: Distributed commit
  - Depends on the model
- Challenge: Concurrency Control Algs
  - Cannot directly use existing CC protocols, e.g., 2PL, MVCC, OCC
- Challenge: Massive concurrency
  - Main difference with multi-core single-node architecture



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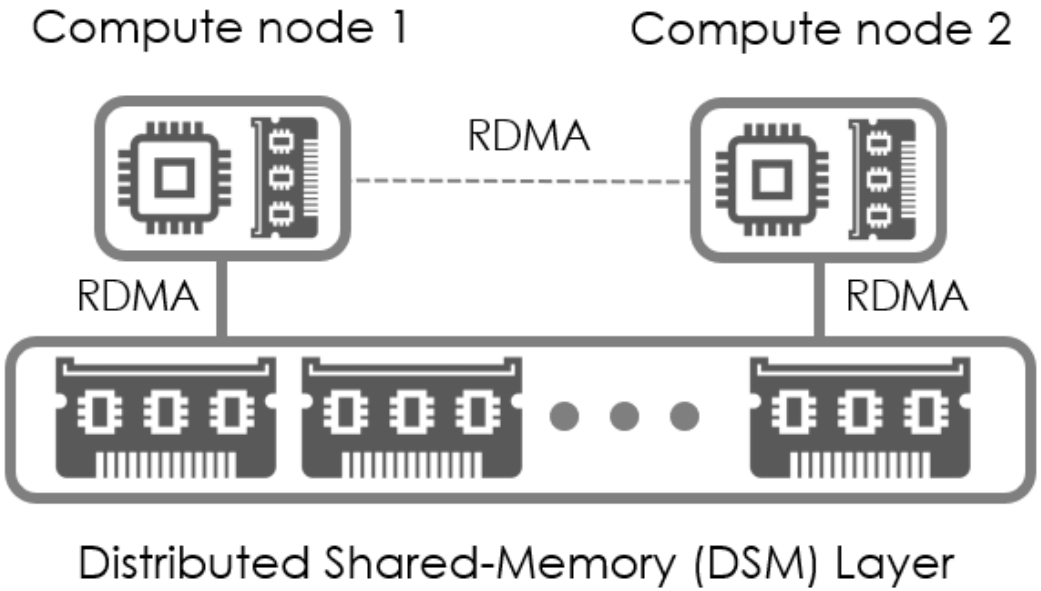
Cache Coherence

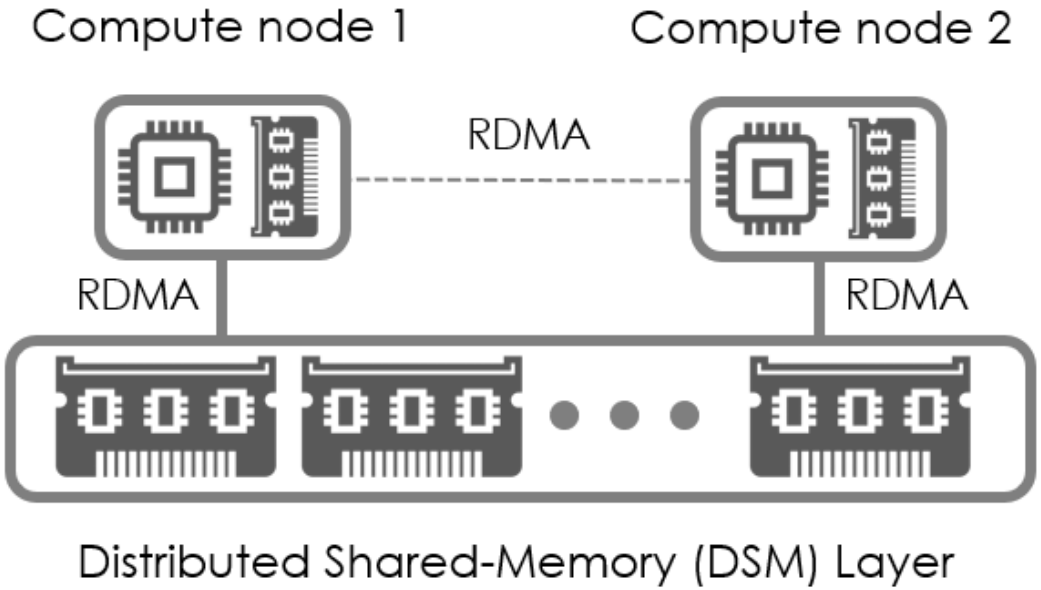
- Do we use the *local buffer* in each compute node?



R. Wang et al. The Case for Distributed Shared Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

Cache Coherence

- Do we use the *local buffer* in each compute node?
  - If yes, need to address cache-coherence problem via software-level → overhead
  - If not, performance hit
    - many remote accesses



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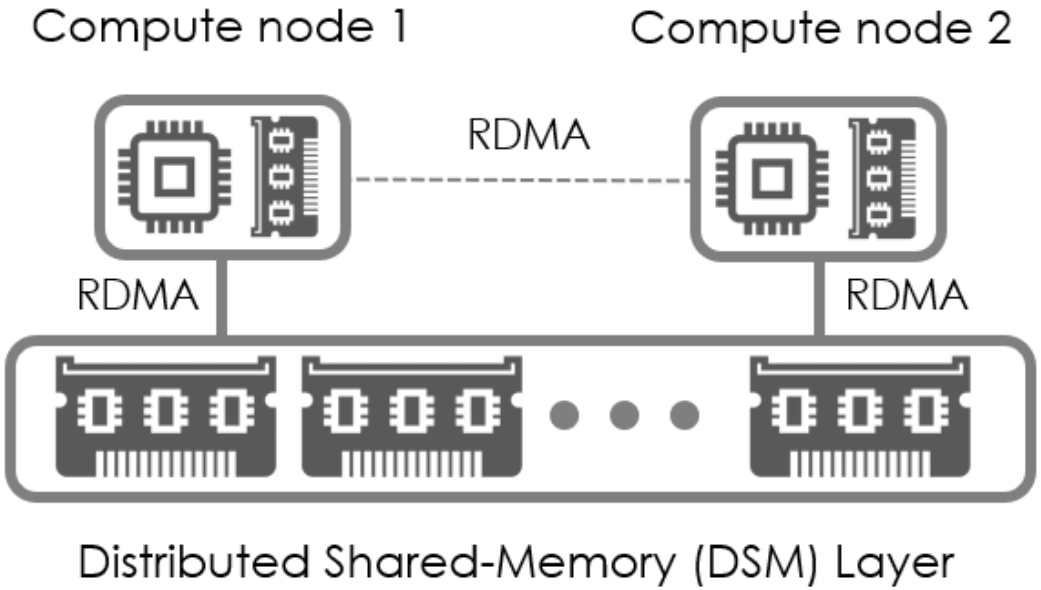
Cache Coherence

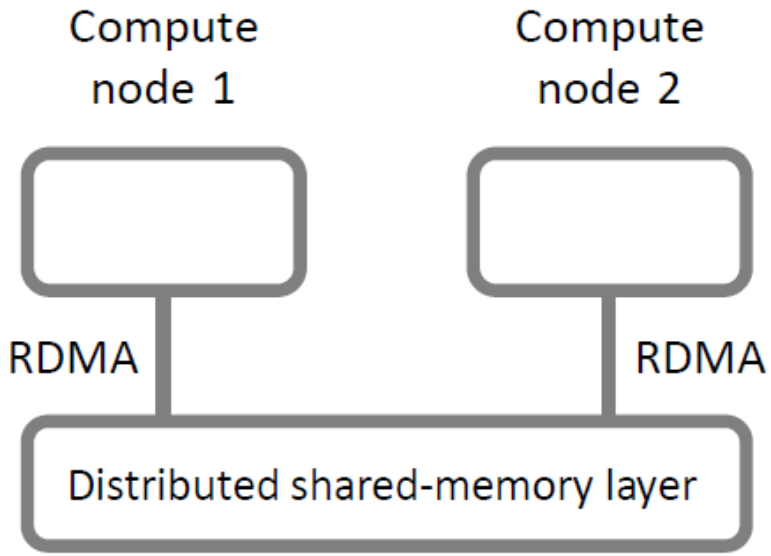
- Do we use the *local buffer* in each compute node?
  - If yes, need to address cache-coherence problem via software-level → overhead
  - If not, performance hit
    - many remote accesses
- Do we use *sharding* between compute nodes?



R. Wang et al. The Case for Distributed Shared Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

Alternative #1: No Sharding, No Cache

- Each compute node reads/writes all data
- But doesn't store any data in local buffer→ No cache coherence issue
- Data pages are stored in DSM



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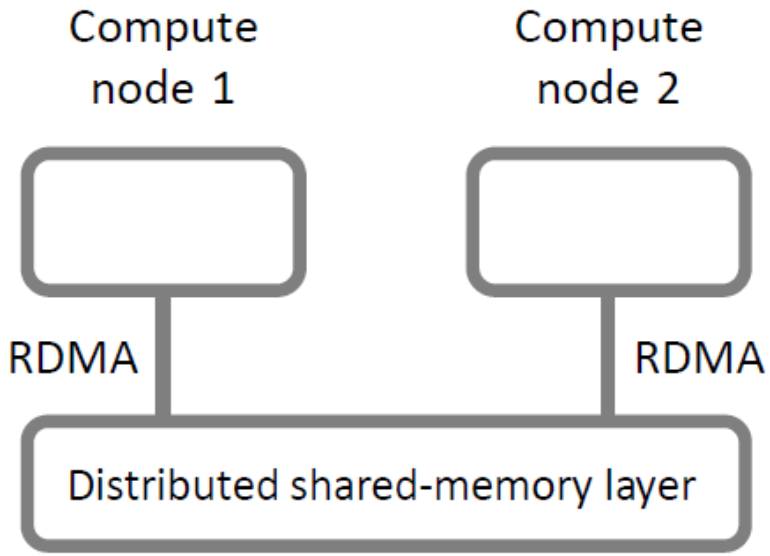
Alternative #1: No Sharding, No Cache

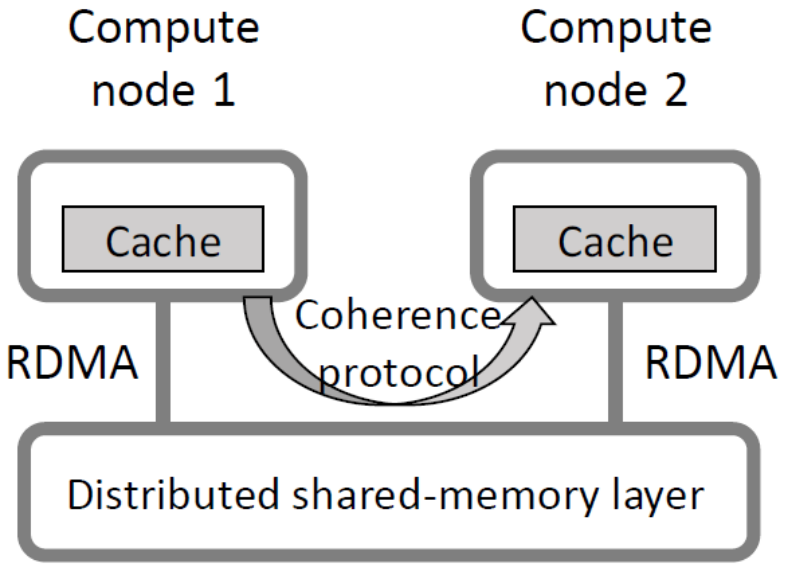
- Each compute node reads/writes all data
- But doesn't store any data in local buffer→ No cache coherence issue
- Data pages are stored in DSM
- All compute nodes use RDMA CAS (compare & swap) to acquire a lock first
- Not realistic → many remote accesses



R. Wang et al. The Case for Distributed Shared Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

Alternative #2: No Sharding, With Cache

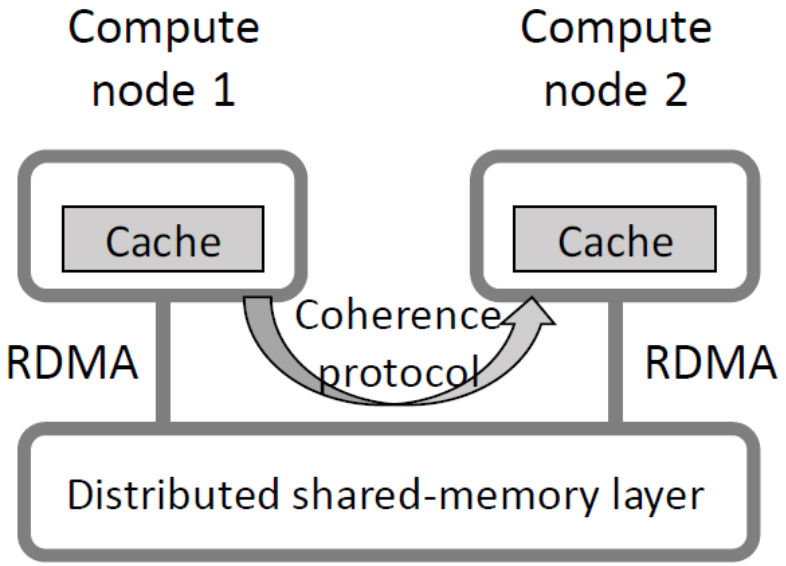
- Each compute node reads/writes all data
- Each compute node caches local data
- How to resolve conflicts?



R. Wang et al. The Case for Distributed Shared Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

Alternative #2: No Sharding, With Cache

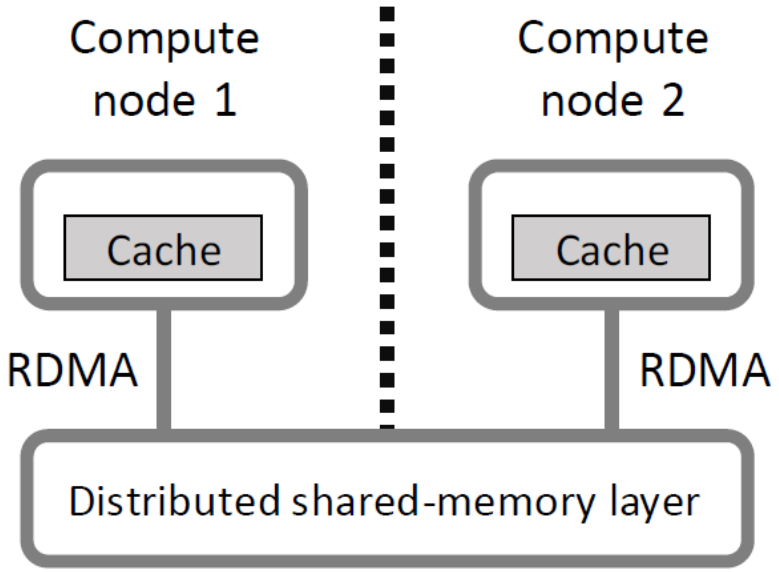
- Each compute node reads/writes all data
- Each compute node caches local data
- How to resolve conflicts?
- Develop a software-level cache coherence protocol
  - Update-based
  - Invalidation-based
- Overhead has to be measured and considered



R. Wang et al. The Case for Distributed Shared Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

Alternative #3: With Sharding, With Cache

- Logical sharding among compute nodes
- Each compute node accesses a partition
- Use local buffer to cache data
- Bypass cache coherence issue
- But depending on workloads



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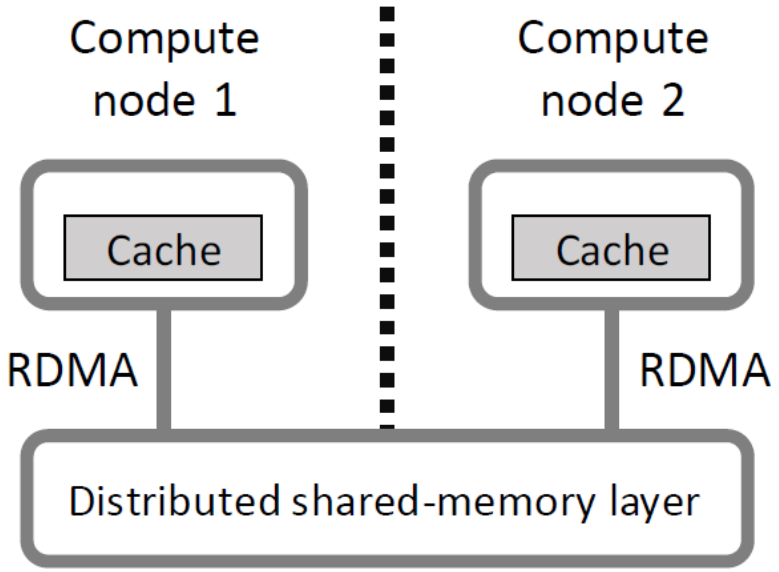
Alternative #3: With Sharding, With Cache

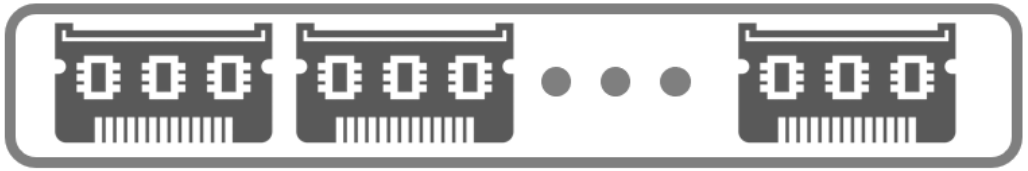
- Logical sharding among compute nodes
- Each compute node accesses a partition
- Use local buffer to cache data
- Bypass cache coherence issue
- But depending on workloads
- Similar to distributed shared-nothing
  - We do logical sharding (not physical sharding)
  - Also, the use of DSM layer can address distributed transaction and data skewness
  - Support elasticity very well



R. Wang et al. The Case for Distributed Shared Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

Distributed Shared-Memory (DSM) Design

- Goal: manage a cluster of memory nodes, and expose necessary APIs to compute nodes
  - Looks like a single unified memory space

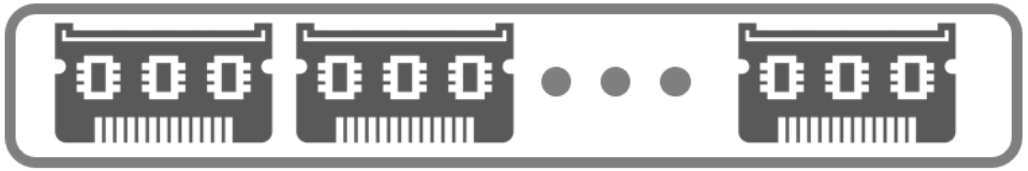


Distributed Shared-Memory (DSM) Layer

R. Wang et al. The Case for Distributed Shared Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

Distributed Shared-Memory (DSM) Design

- Goal: manage a cluster of memory nodes, and expose necessary APIs to compute nodes
  - Looks like a single unified memory space
- Challenge: Durability & Availability
- Challenge: Abstract APIs
  - Memory access APIs (also memory space representation)
  - Data transmission APIs (for RDMA)
  - Function offloading APIs (for DBMS ops)

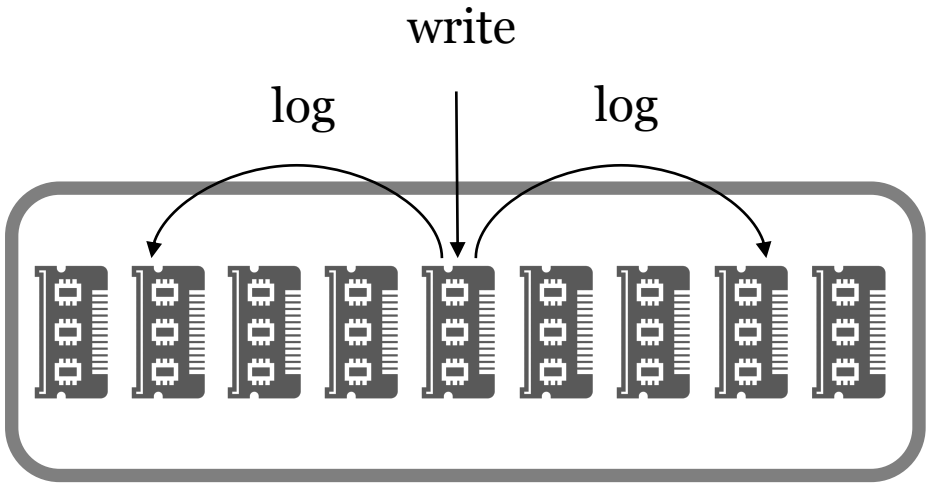


Distributed Shared-Memory (DSM) Layer

R. Wang et al. The Case for Distributed Shared Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

Durability & Availability

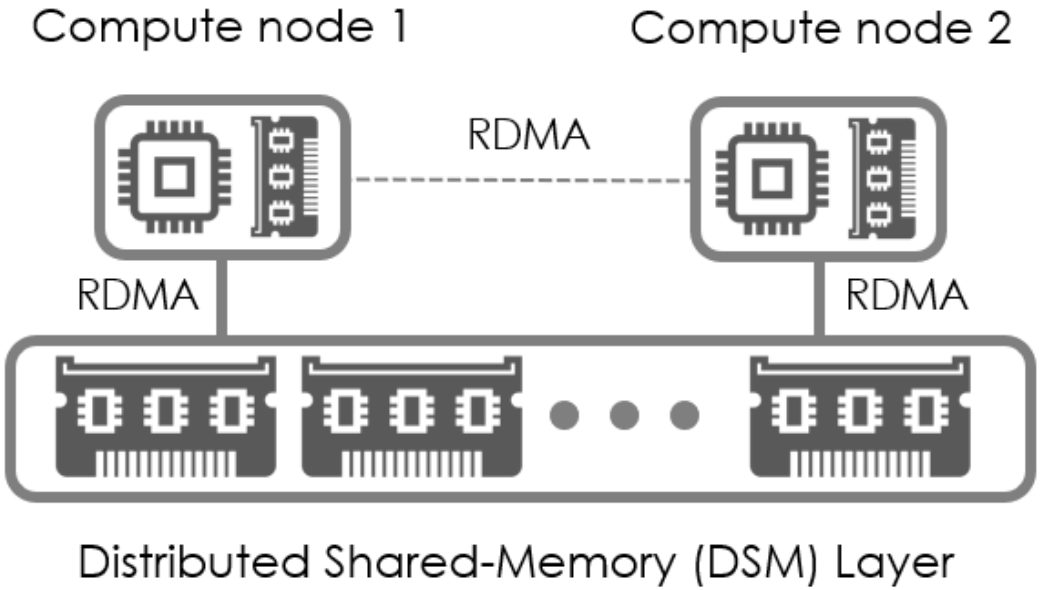
- Memory-based system
- Replication of data
  - Additional memory space + write performance
- Log-based solution (RAMCloud[1])
  - Separate logs from data (log store + data store)
  - Only logs are replicated in three memory nodes
    - A transaction is committed once all the logs are replicated and acknowledged
    - Data pages are asynchronously materialized
  - Data pages are stored only once in memory
  - Periodically checkpoint data pages to shared-storage to improve availability



[1] J. Ousterhout, et al. The Case for RAMClouds: Scalable High-Performance Storage Entirely in DRAM, *Proc. SIGOPS*, 2009.

Index Design Challenges

- Challenge: Leveraging RDMA characteristics (e.g., RDMA primitives)
- Challenge: How to use the buffer memory in compute nodes?
- Challenge: Leveraging RDMA byte-addressability
- Challenge: Leveraging near-data computing
- Challenge: How to support multi-node concurrent accesses?



R. Wang et al. The Case for Distributed Shared Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

Rethinking Existing Indexes

Disk-based indexes

- E.g., B-tree, LSM-tree
- Not designed for RDMA (e.g., which primitive)
- Not optimized for byte-addressability
- Not leveraging near-data computing
- Multi-node concurrent accesses
  - E.g., use a single lock for both read and write or use read-write locks?

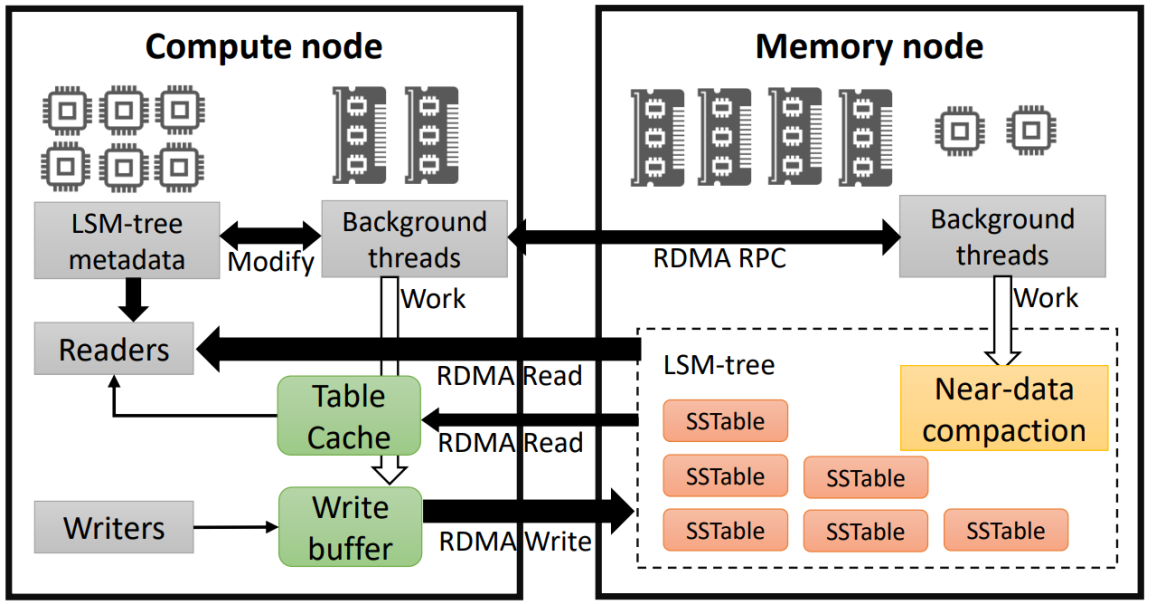
Memory-based indexes

- E.g., Bw-tree, Mass-tree, ART
- Not designed for RDMA (e.g., which primitive)
- Not leveraging local buffer
- Not leveraging near-data computing
- Multi-node concurrent accesses
  - E.g., lock-free vs. lock-based

R. Wang et al. The Case for Distributed Shared Memory Databases with RDMA-Enabled Memory Disaggregation, *Proc. VLDB*, 2022.

dLSM

- Compute node: MemTable, immutable, index blocks, bloom filters
- Memory node: SSTables (memory-optimized)
- One-sided RDMA read/write
- Reduce software overhead
  - Synchronization
  - Flushing
- Near-data compaction
- Optimize for byte-addressability
  - Can access a single KV pair



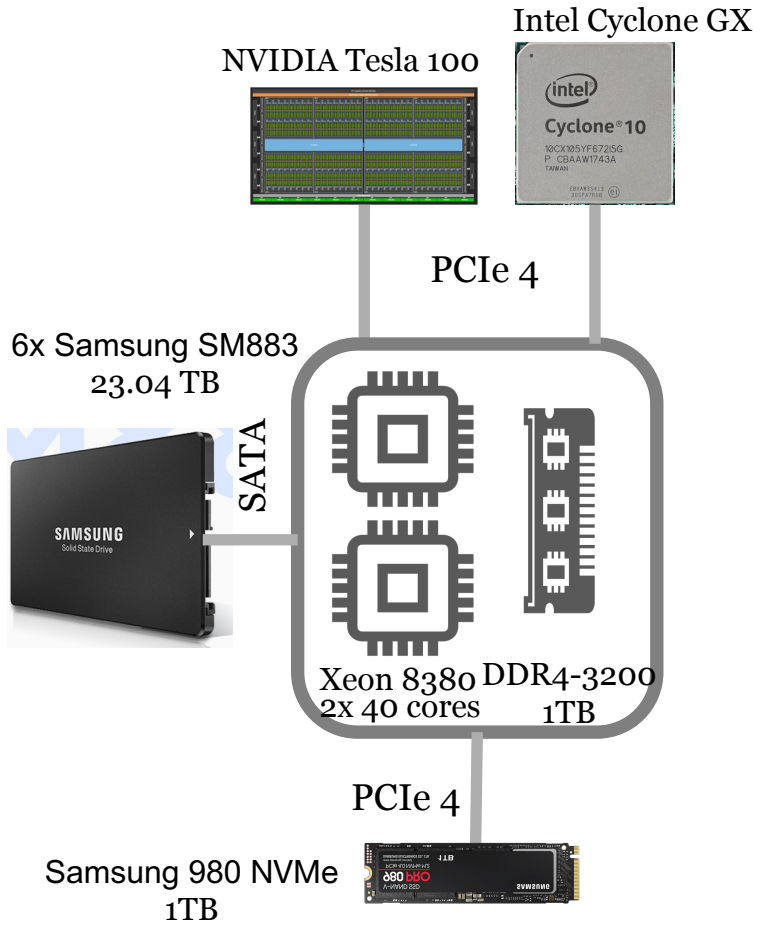
R. Wang et al. dLSM: An LSM-based Index for RDM-Enabled Memory Disaggregation, *Proc. ICDE*, 2023.

DISAGGREGATED HETEROGENEOUS PLATFORM

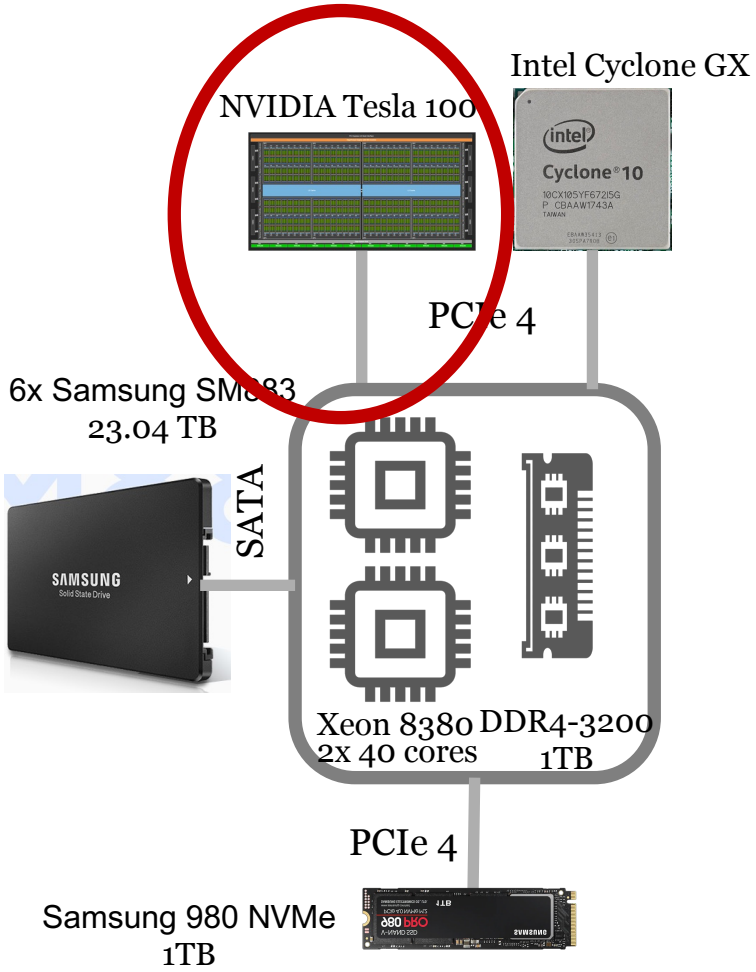
Heterogeneity

Case for Heterogeneous Computing

- Computing platforms are already heterogeneous
- Remember that CPU is not keeping up
- Data parallel computations of new workloads perform well on GPUs
- FPGAs are more flexible and can serve to experiment with solutions
- High volume demand for same task might be best met by ASICs



Data Management over GPU/CPU-GPU



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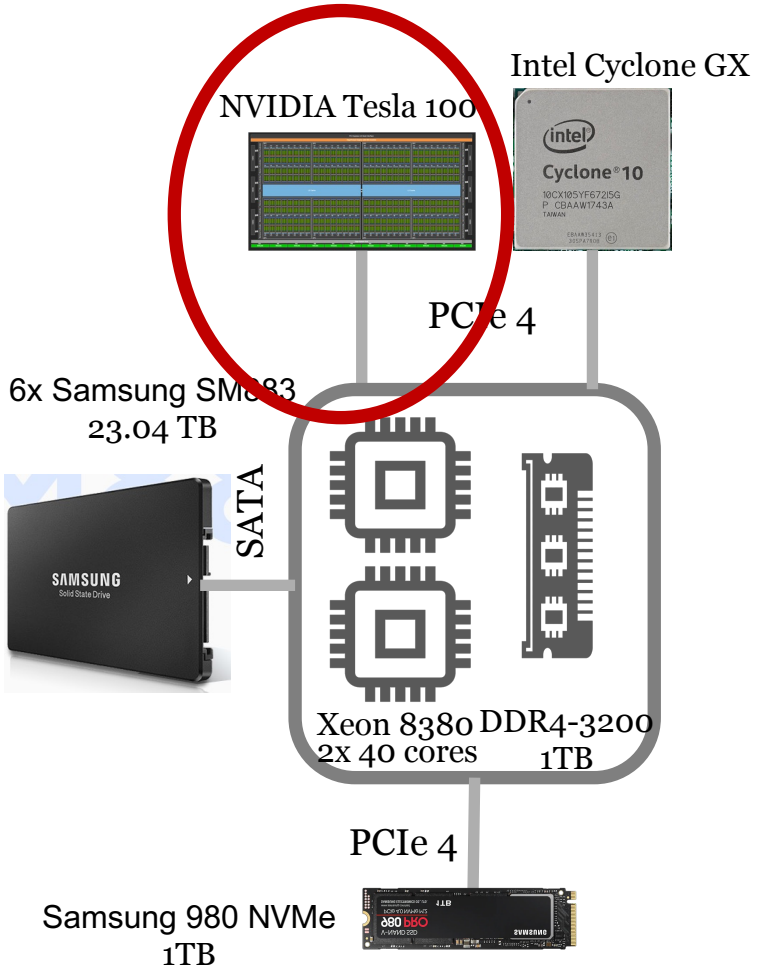
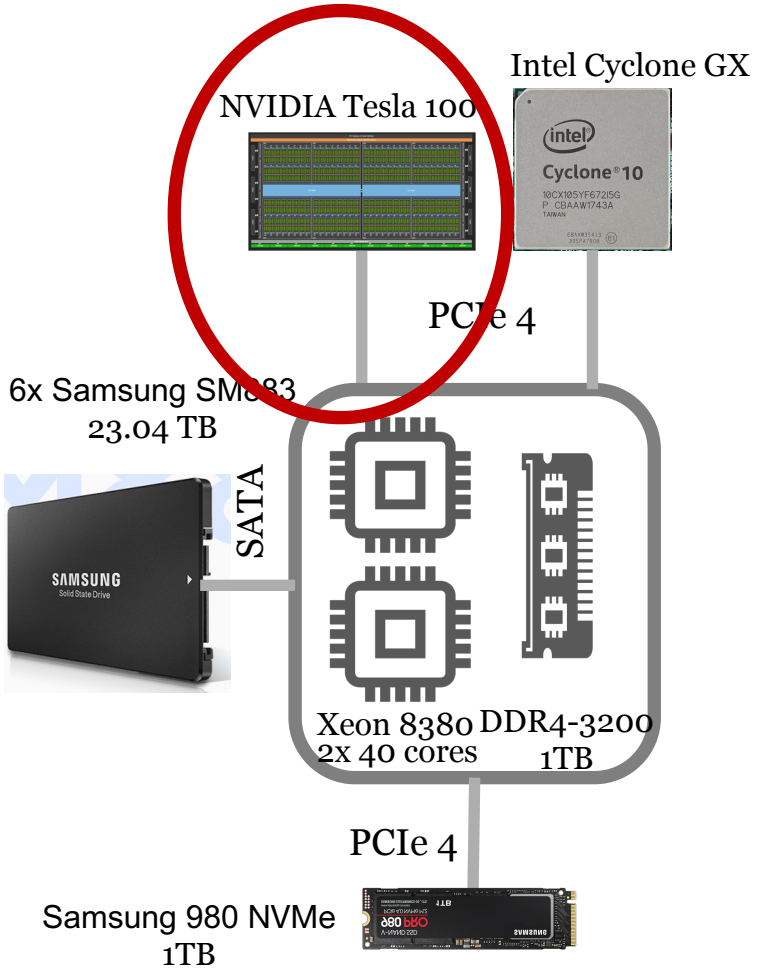


Two approaches

Data Management over GPU/CPU-GPU

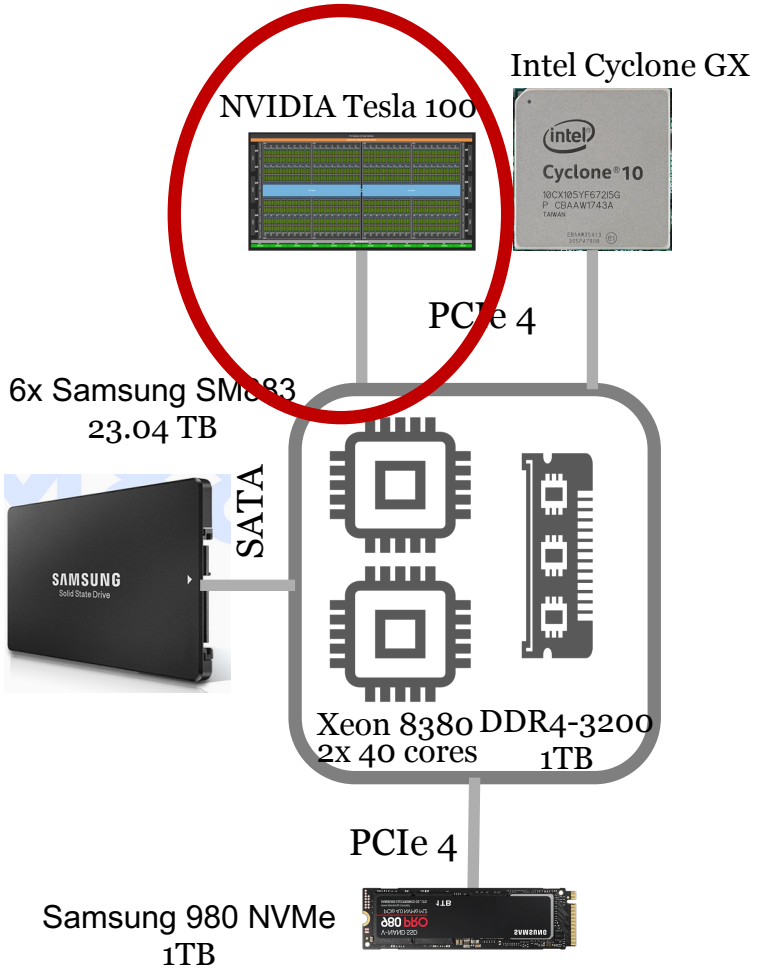


Two approaches

- Transfer data to GPU on-demand[1]
  - PCIe bandwidth is an issue
  - PCIe bottleneck sometimes causes performance < optimized CPU implementations
  - Store working set directly on GPU[2]

[1] J. Li et al. HippogriffDB: Balancing I/O and GPU Bandwidth in Big Data Analytics, *Proc. VLDB*, 2016.
[2] A. Shanbhag, S. Madden and X. Yu. A Study of the Fundamental Performance Characteristics of GPUs and CPUs for Database Analytics, *Proc. SIGMOD*, 2020.

Data Management over GPU/CPU-GPU

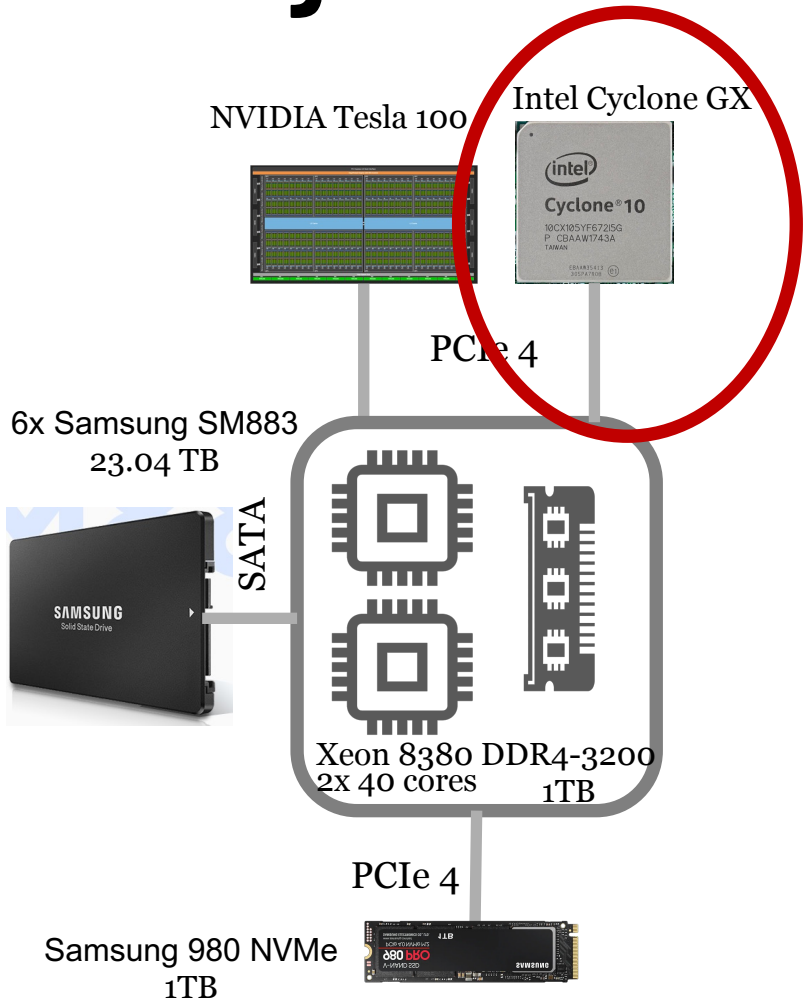


Two approaches

- Transfer data to GPU on-demand[1]
  - PCIe bandwidth is an issue
  - PCIe bottleneck sometimes causes performance < optimized CPU implementations
  - Store working set directly on GPU[2]
- CPU-GPU heterogeneous processing[3,4]
  - Design more complicated
  - Data placement – treat GPU memory as cache[4]
  - Finer granularity cache → more complex query execution
  - Cost model to decide where to execute what

[3] P. Chrysogelos et al. HeatExchange: Encapsulating Heterogeneous CPU-GPU Parallelism in JIT Compiled Engines, *Proc. VLDB*, 2019.
[4] B. W. Yogatama, W. Gong and X. Yu. Orchestrating Data Placement and Query Execution in Heterogeneous CPU-GPU DBMS, *Proc. VLDB*, 2022.

Data Management over FPGA/CPU-FPGA



"FPGAs … configure different parts of the design space offering advantages that other current options do not have:

- line rate processing;
- enabling processing streams of data out of the network, disks, or memory without performance loss;
- architectural flexibility in that they can be inserted in places where the other type of processor cannot be used such as in NICs, in storage, in memory, etc. …; and
- the customizable nature of reconfigurable computing with the FPGA serving equally well to accelerate network function virtualization, data reorganization in a database, or to accelerate joins."

W. Jiang, D. Korolija and G. Alonso. Data Processing with FPGAs on Modern Architectures, *Proc. SIGMOD*, 2023.

FINAL WORDS

Environment is Getting Interesting

- Other h/w developments that can help (but I don't know much about):
  - Tensor Processing Unit (TPU)
  - Data Processing Unit (DPU)
  - Non-Volatile Memory (NVM)
- Design space is varied and large
  - But start somewhere

UNIVERSITY OF WATERLOO | DSg Data Systems Group

Thank you