ISOTDAQ

International School of Trigger and Data Acquisition

Storage systems for DAQ

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Storage Examples in Bytes

CERN vs. YouTube

Who's storing more data?

4K video stream
(~ 4 MB/s)

kilo 10^3 mega 10^6 giga 10^9 tera 10^{12} peta 10^{15} exa 10^{18}

Storage Examples in Bytes

Google global storage
(10-15 EB)

YouTube

YouTube to storage
(~ 8-50 GB/s)

YouTube to storage
(~ 240-10^3 PB/year)

"700'000 hours of content uploaded every day"

4K video stream
(~ 4 MB/s)

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DUNE

DUNE to storage
(~ 250 MB/s)

DUNE pre-trigger
(~ 1.5 TB/s)

DUNE to storage
(~ 7.5 PB/year)

4K video stream
(~ 4 MB/s)

kilo 10^3 — mega 10^6 — giga 10^9 — tera 10^{12} — peta 10^{15} — exa 10^{18}

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(~ 240-10^3 PB/year)

ATLAS EXPERIMENT

ATLAS to storage
(~ 1-5 GB/s)

ATLAS pre-trigger
(~ 60 TB/s)

ATLAS to storage
(~ 40 PB/year)

DUNE

DUNE to storage
(~ 250 MB/s)

DUNE pre-trigger
(~ 1.5 TB/s)

DUNE to storage
(~ 7.5 PB/year)

4K video stream
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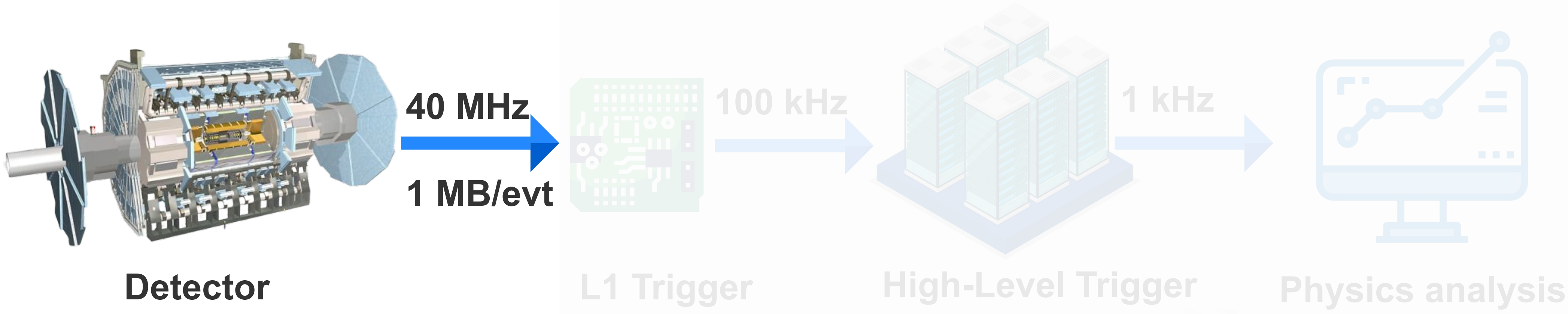
Outline

- Why are storage systems relevant for DAQ ?
- Storage concepts
- Technology overview
  - HDD, SSD, NVM and DRAM
- Performance benchmarking
- Redundant and Distributed systems
- Storage challenges for the future
  - Storage system for the DUNE-DAQ
- Conclusion

Why are storage systems relevant for DAQ ?

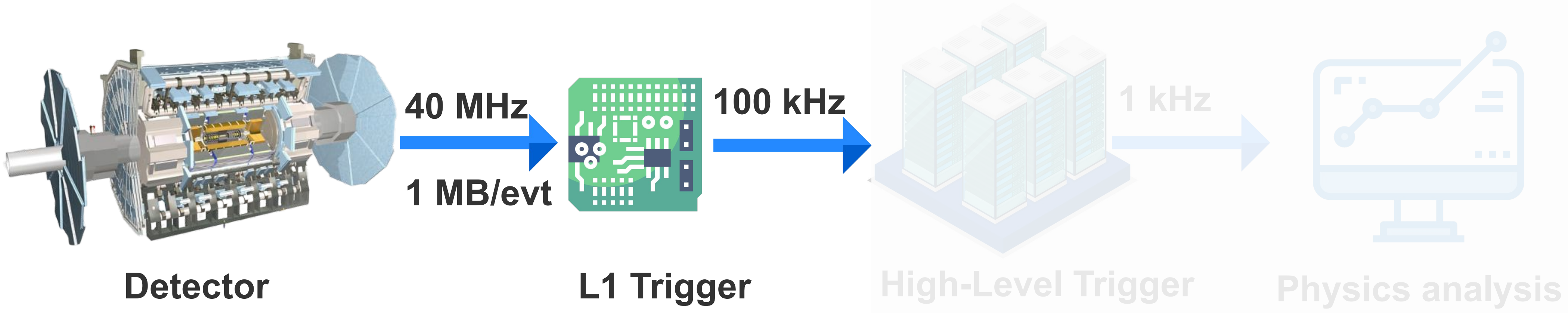
TDAQ pipeline



- Not all the data can be stored:
  - Lack of storage resources
  - Not enough (offline) processing power

Why are storage systems relevant for DAQ ?

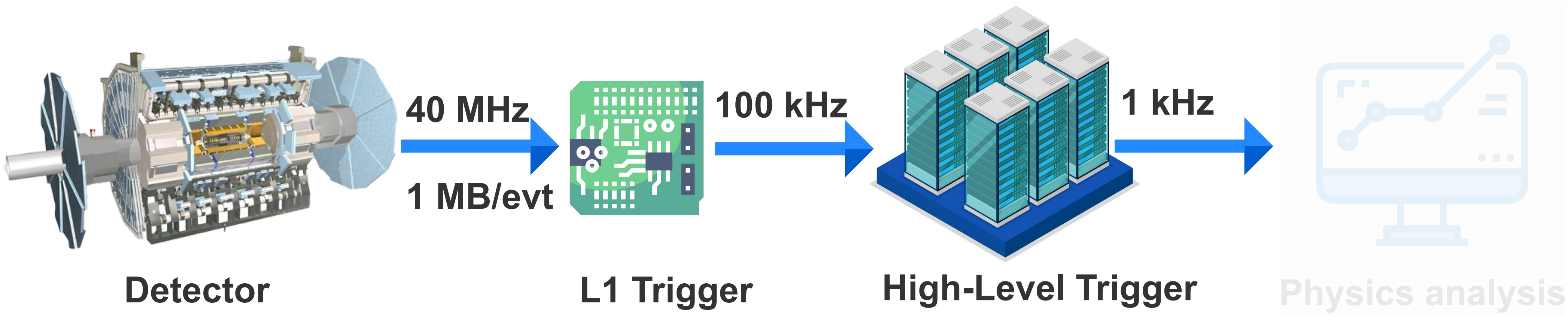
TDAQ pipeline



- Hardware based selection using custom electronics and FPGAs

Why are storage systems relevant for DAQ ?

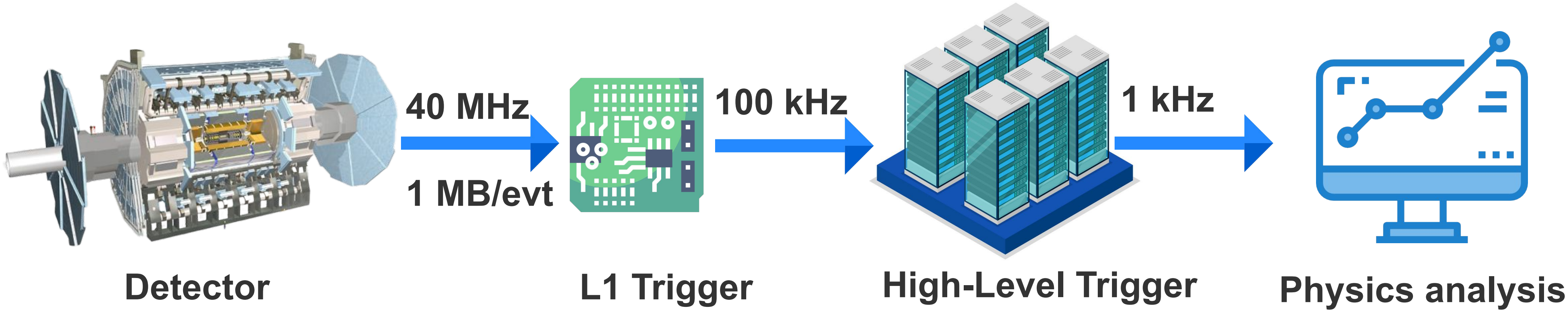
TDAQ pipeline



- Software based filtering using a local server farm

Why are storage systems relevant for DAQ ?

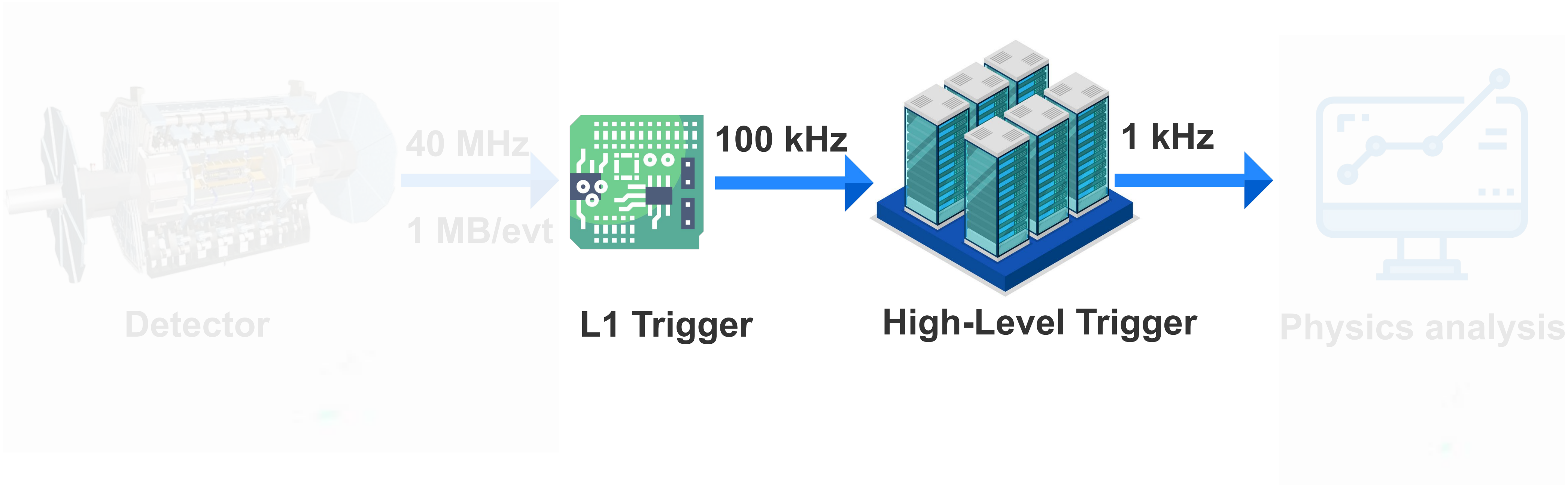
TDAQ pipeline and physics analysis



- Analysis runs global algorithms on distributed (remote) compute resources

Why are storage systems relevant for DAQ ?

TDAQ pipeline - Online data taking ("DAQ")



Focus on the storage systems **for DAQ**

DAQ takeaway
Online vs Offline

- Storage systems ensure that data is stored and physics results can be produced!

- DAQ requirements are different from offline analysis:
  - Storage used to buffer data:
    Absorbs rate fluctuations from the rest of the system
  - Access pattern: Continuous stream of data flow
    in and out the storage system
  - **Throughput** and **latency constraints**
  - Technology choice affected by **total exaffpected data**

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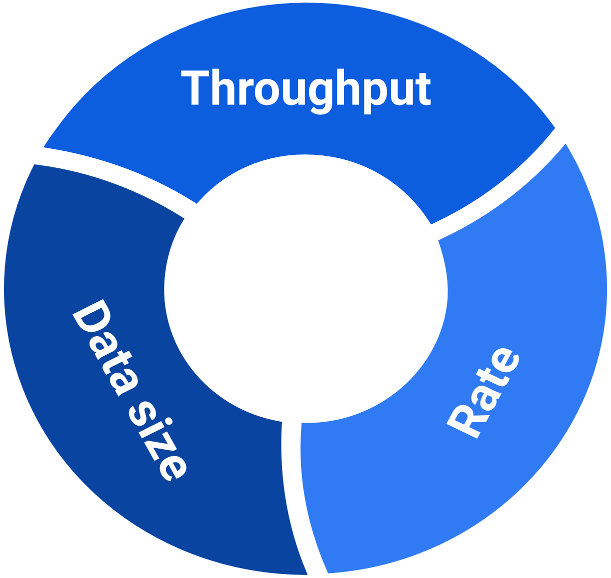

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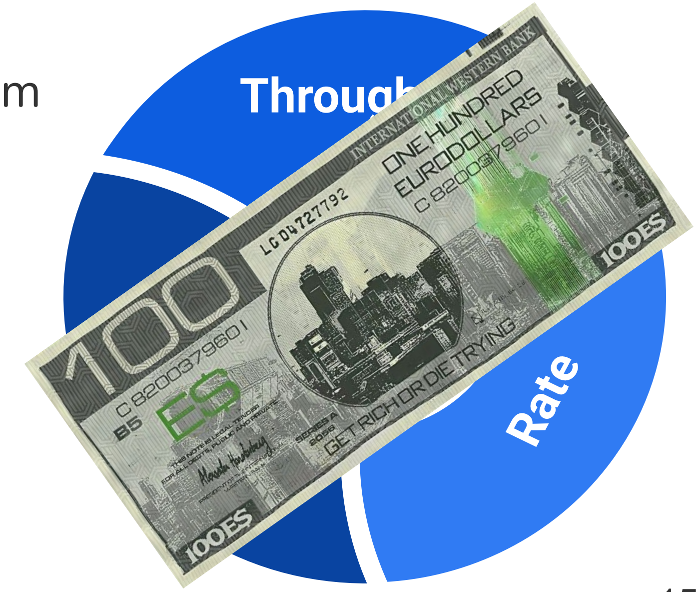
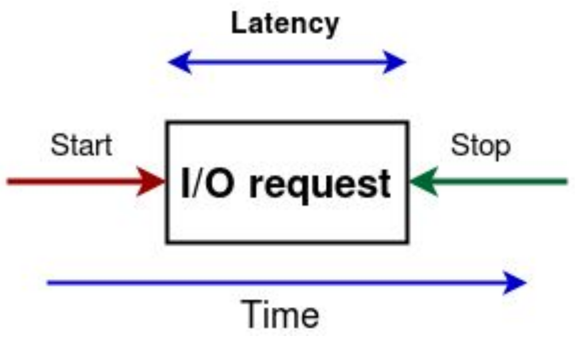


and cost!

Storage concepts and Technology overview

Storage concepts
Some definitions



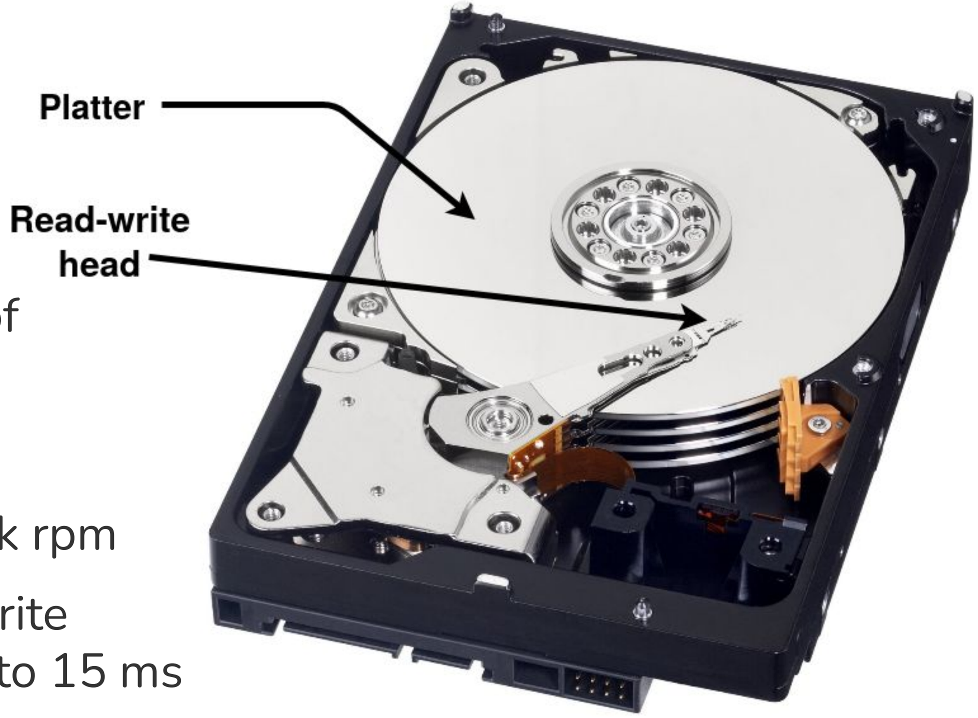
- **I/O:** input/output operation
- **Access pattern:** sequential/random read or write
- **Latency**: time taken to respond to an I/O. Usually measured in ms or in µs
- **Rate:** number of I/O per second to a storage location (**IOPS**)
- **Blocksize:** size in bytes of an I/O request
- **Bandwidth**: product of I/O block size and IOPS

Bandwidth = [I/O block size] x [IOPS]

Hard drives (HDD)

Quick introduction

- Electromechanical device
- Circular rotating platter divided into millions of magnetic components where data is stored
- Typical rotational speed of HDDs:
    - 5400 rpm, **7200 rpm**, 10k rpm and 15k rpm
- **Seek time:** time required to adjust the read-write head on the platter. Typical values: from 3 ms to 15 ms
- **Rotational latency:** time needed by the platter to rotate and position the data under the read-write head. Typical values: from 7 ms to 2 ms.

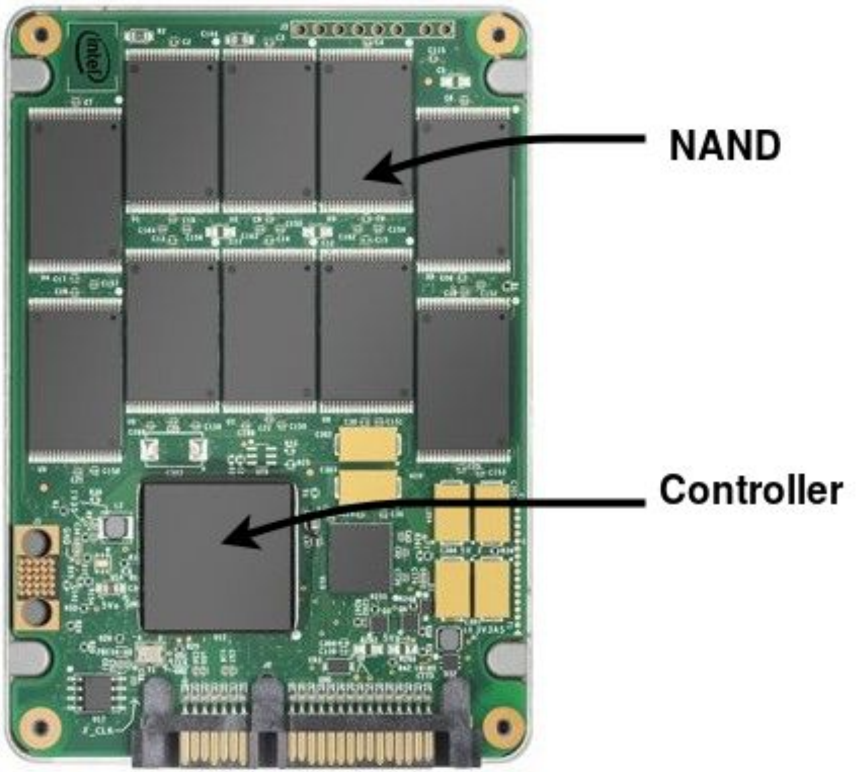


$$IOPS = \frac{1}{\text{Avg. seek} + \text{Avg. latency}}$$

Solid state drives (SSD)
Quick introduction

Floating gate transistors

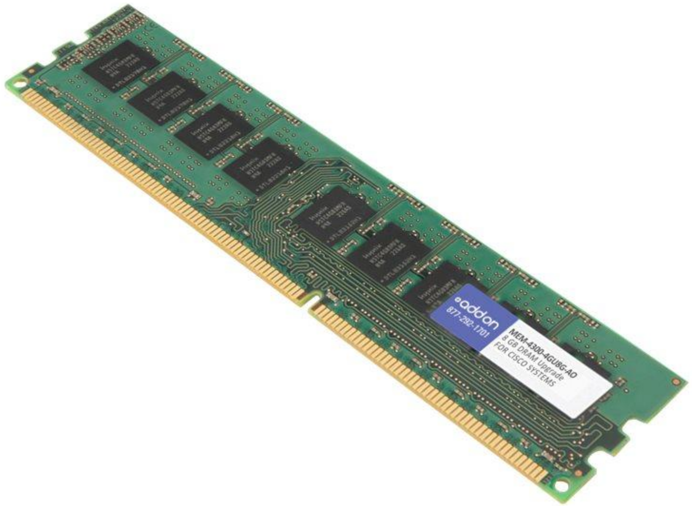
- **Architecture**:
  - NAND flash chipset: store data
  - Controller: caching, load balancing and error handling
- Capacity limited to number of NAND chipsets a manufacturer is able to insert into a device
- (Typically) better performance compared to HDDs
  - There is no mechanical component
  - Reduced latency and no seek time
- Optimized controller and communication technology for higher bandwidth devices
  - NVM Express (NVMe) SSD

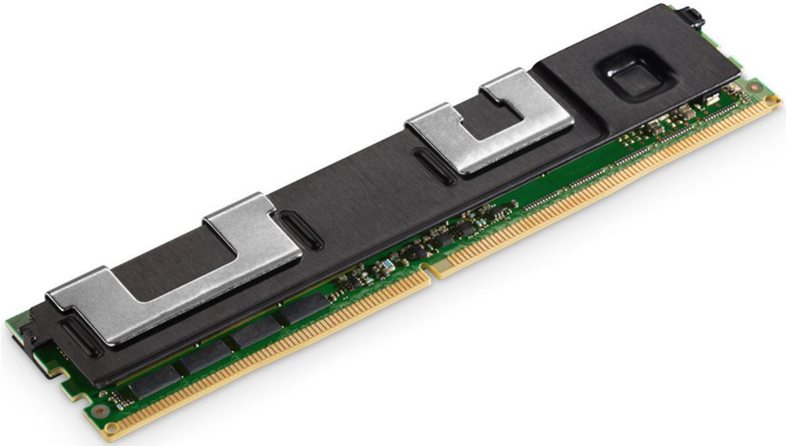


DRAM and Non-Volatile Memory

Quick introduction

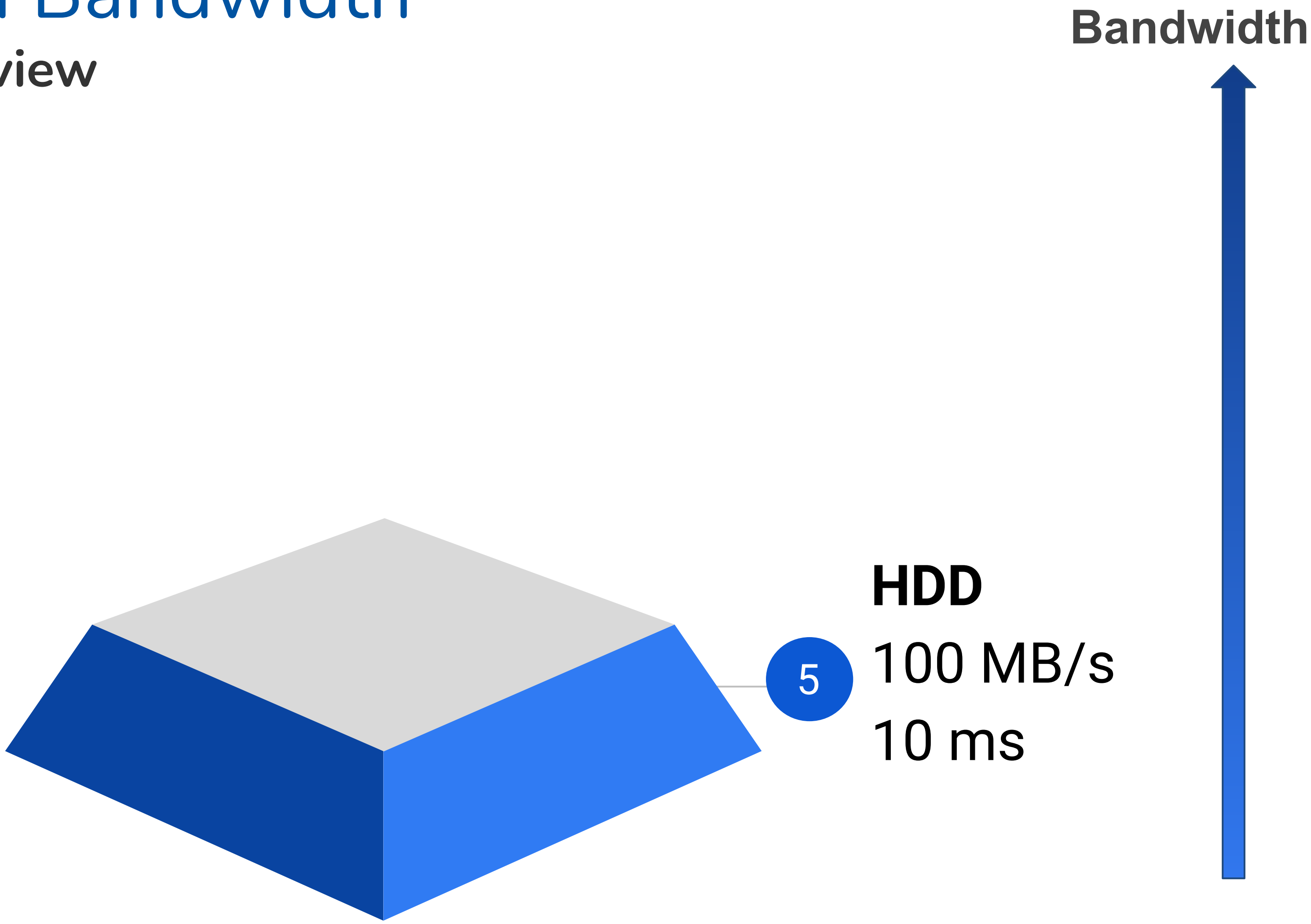
- **DRAM (Dynamic Random Access Memory)**
  - Semiconductor memory technology
  - Data is not persisted, only temporary storage cells (capacitors and transistors)
  - Low latency (0.1 µs)
- **Non-volatile memory (NVM)**
  - Hold data even if device is turned off
  - Higher storage capacity than DRAM
  - Latency (1 µs)
  - 3D XPoint technology (Intel and Micron, 2015)





Latency and Bandwidth

Technology overview



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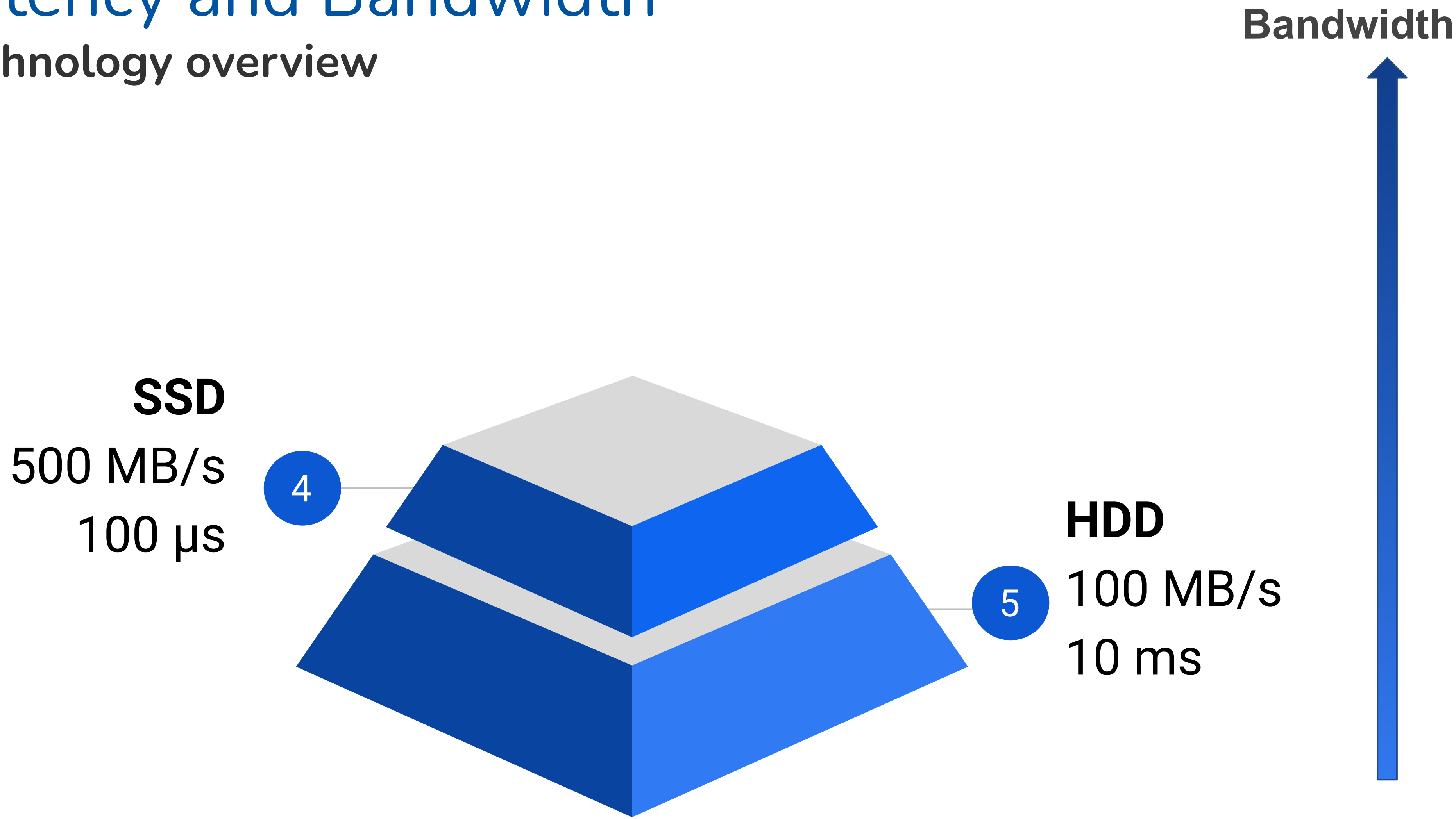

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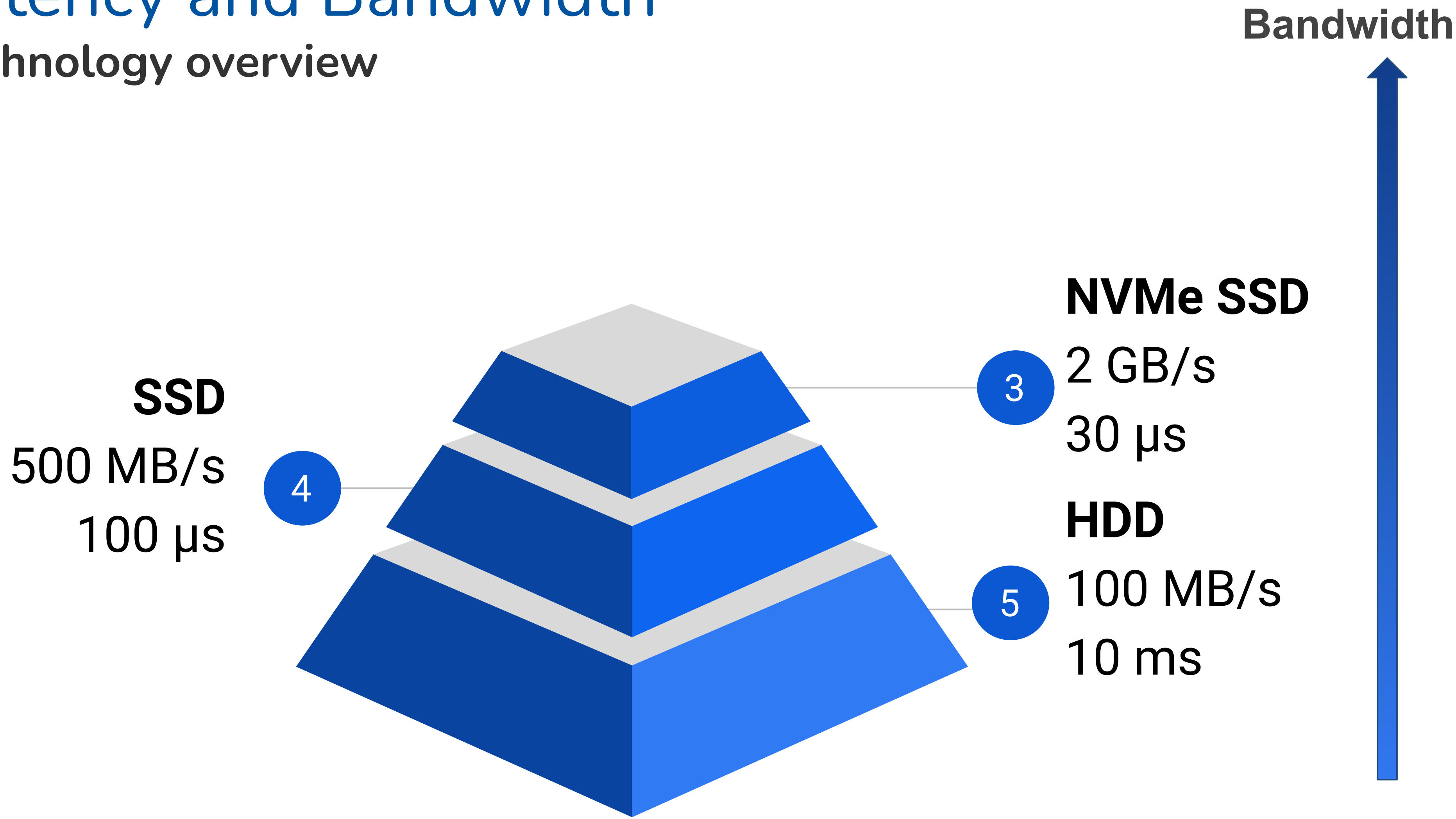

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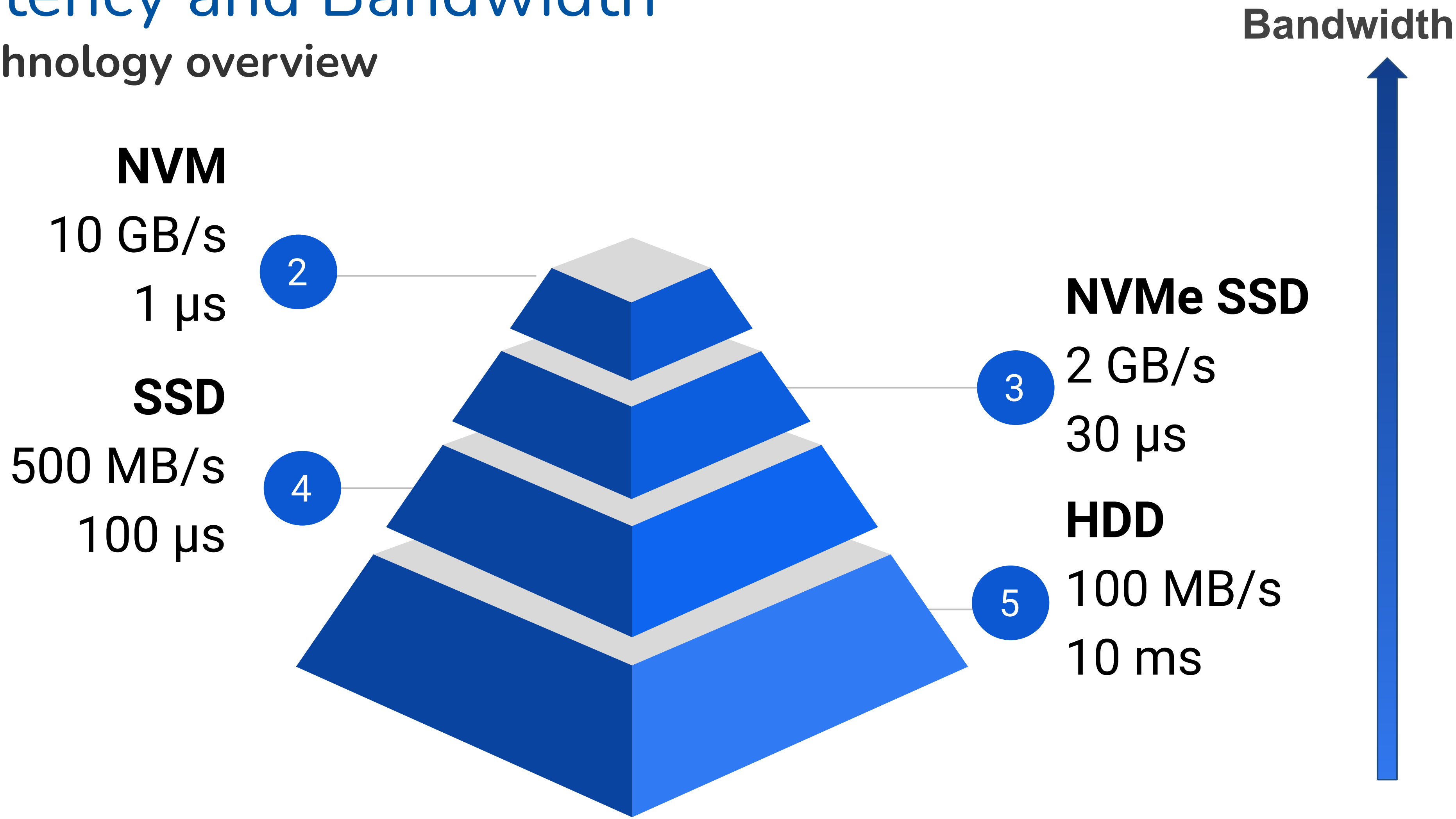

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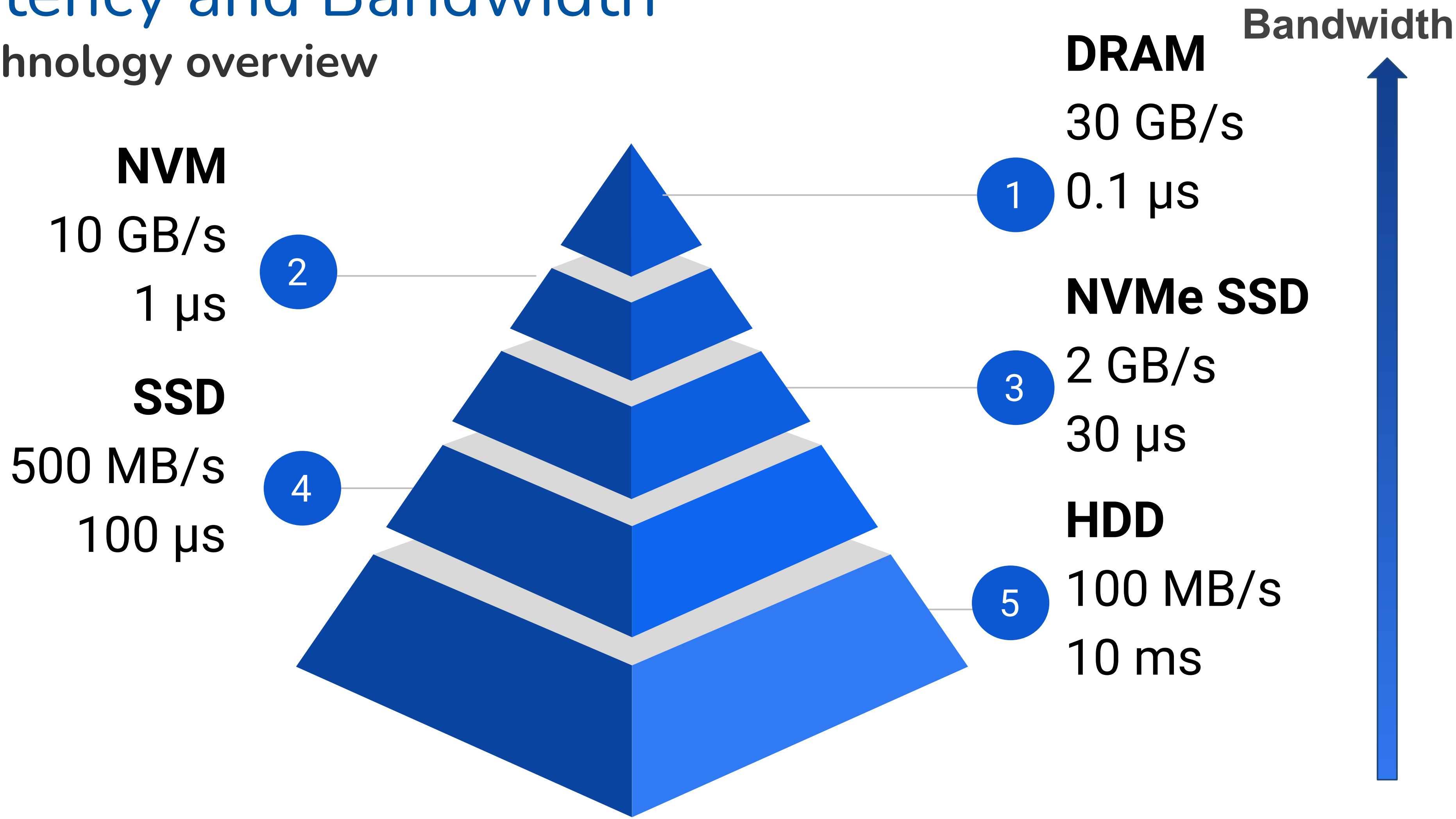
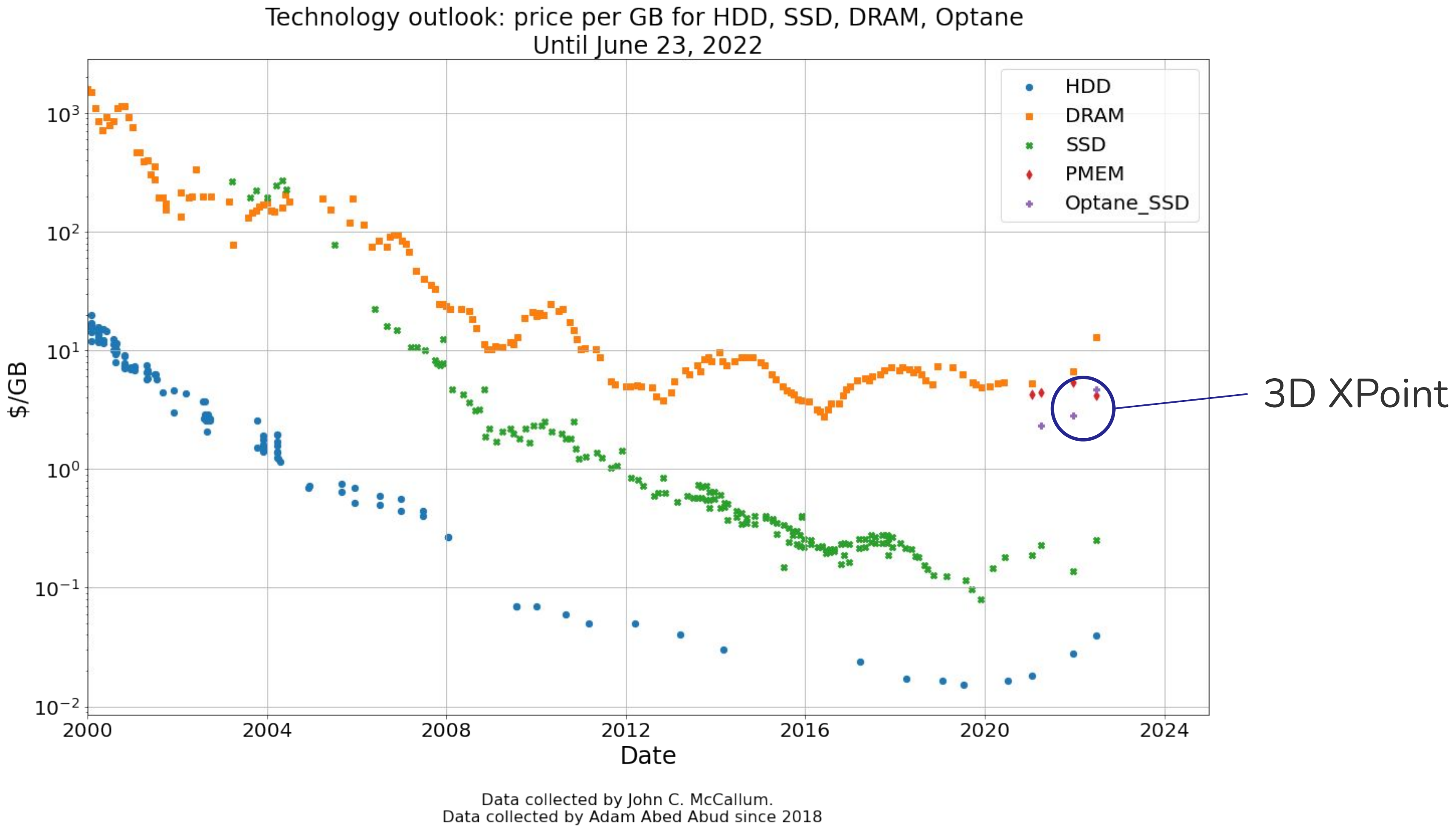


Market trend for storage technologies

Price per GB for HDD, SSD, Flash and RAM



Storage benchmarking

DD

- Linux tool to copy data at the block level
- Usage:
  - `dd if=/path/to/input/file of=/path/to/output/file bs=block_size count=amount_blocks`
- Avoid operating system cache by adding **oflag=direct** option

```
[student@storage_lecture]$ dd if=/dev/zero of=deleteme bs=1M count=1000
1000+0 records in
1000+0 records out
1048576000 bytes (1.0 GB, 1000 MiB) copied, 3.67626 s,  285 MB/s
```

Storage benchmarking

Flexible I/O (FIO)

- Advanced tool for characterizing I/O devices
- Usage:
    - **fio --rw**=<opt1> **--bs**==<opt2> **--size**=<opt3> **--filename**=<opt4> **--direct**=<opt5> **--ioengine**=libaio **--name**=isotdaq

```
[student@storage_lecture]$ fio --rw=write --bs=1M --size=1G --filename=deleteme
--direct=0 --ioengine=libaio --name=isotdaq

fio-3.12
Starting 1 process
isotdaq : Laying out IO file (1 file / 1024MiB)
… … …
Run status group 0 (all jobs):

  WRITE: bw=276MiB/s (282MB/s), 276MiB/s-276MiB/s (282MB/s-282MB/s), io=1024MiB
(1074MB), run=4424-4424msec
```

Redundant Array of Inexpensive Disks (**RAID**)

Redundancy and fault tolerance

- Multiple physical disk drives are logically grouped into one or more units to increase data performance and/or data redundancy
- Invented in 1987 by researchers from the University of California
- Most common RAID types: RAID 0, RAID 1, RAID 5, RAID 10
- **Fault tolerance** guaranteed by using **parity** as an error protection scheme
  - Based on the XOR logic operation
  - For series of XOR operations, count the number of occurrences of 1:
    - If result is even then bit parity is 0
    - If result is odd then bit parity is 1

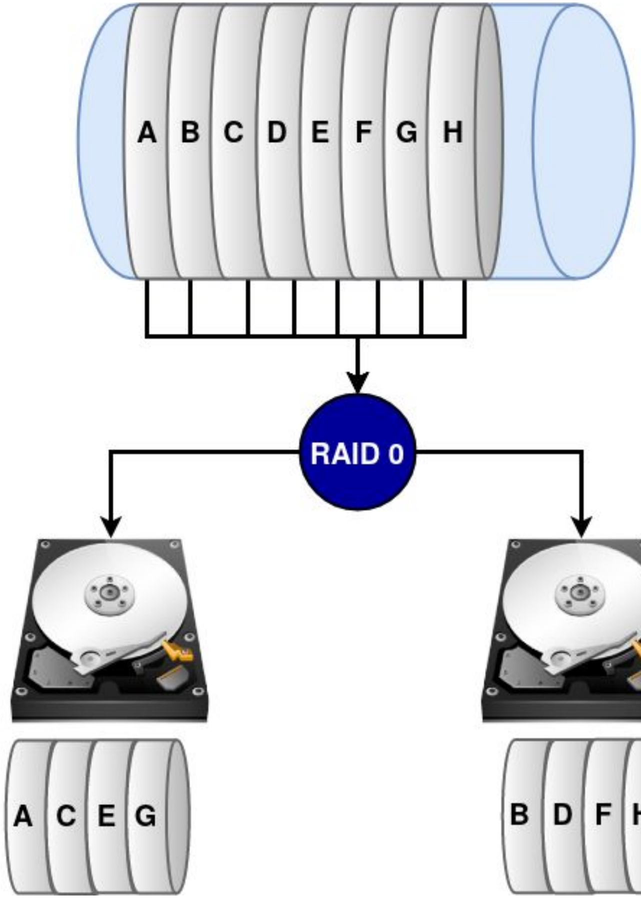
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Redundant Array of Inexpensive Disks (**RAID**)

RAID 0 - Striping

typically O(10) kB

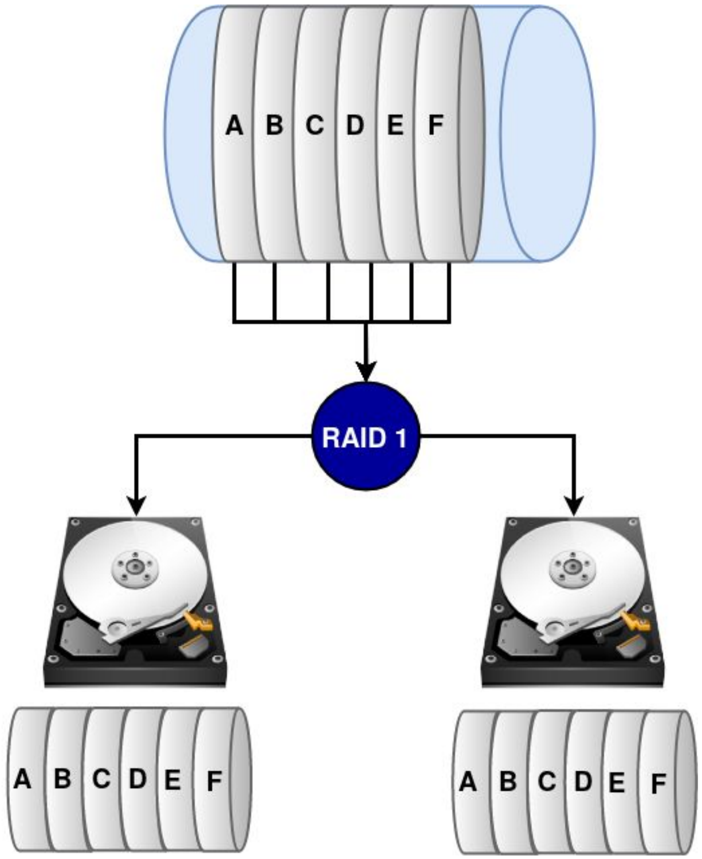
- Data divided in blocks and striped across multiple disks
- **Not fault tolerant** because data is not duplicated
- Speed advantage
    - Two disk controllers allow to access data much faster



Redundant Array of Inexpensive Disks (**RAID**)

RAID 1 - Mirroring and Duplexing

- Data divided in blocks and <u>copied</u> across multiple disks
- **Fault tolerant** because of data mirroring
    - Each disk has the same data
- **Disadvantage**: usable capacity is half of the total



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A crash course on bit parity

Example for a “3-bit” hard drive

Disk 1	Disk 2	Disk 3	Count	Parity
0	1	1		
1	0	0		
1	1	0		

A crash course on bit parity

Example for a “3-bit” hard drive

Disk 1	Disk 2	Disk 3	Count	Parity
0	1	1	2	0
1	0	0	1	1
1	1	0	2	0

A crash course on bit parity

Disk failure

Disk 1	Disk 2	Disk 3	Count	Parity
0	1	1	2	0
1	0	0	1	1
1	1	0	2	0

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A crash course on bit parity

Example for a “3-bit” hard drive

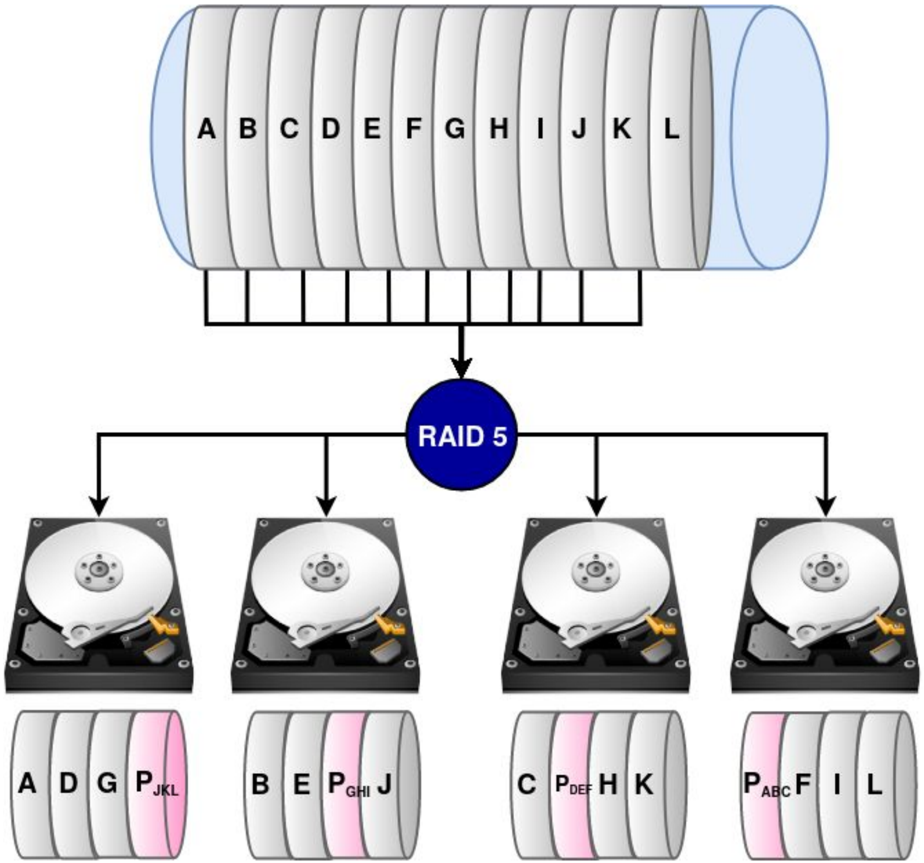
Disk 3
1
0
0

Disk 1	Disk 2	Parity	Count	Disk 3
0	1	0	1	1
1	0	1	2	0
1	1	0	2	0

Redundant Array of Inexpensive Disks (**RAID**)

RAID 5 - Striping with parity

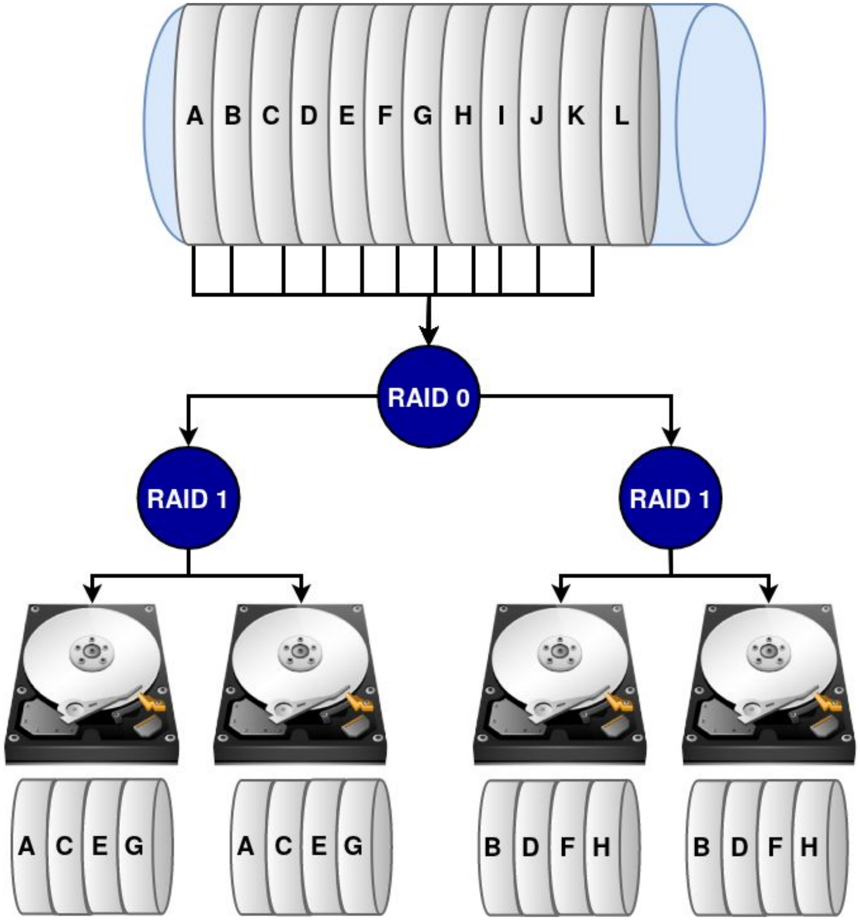
- Requires 3 or more disks
- Data is not duplicated but **striped** across multiple disks
- Fault tolerant because **parity** is also striped with the data blocks
- Larger capacity provided compared to RAID 1
- Disadvantage: an entire disk is used to store parity



Redundant Array of Inexpensive Disks (**RAID**)

RAID 10 = RAID 1 + RAID 0

- Requires a minimum of 4 disks
- Data is **striped** (RAID 0)
- Data is duplicated across multiple disks (RAID 1)
- **Advantage**: fault tolerance and higher speed
- **Disadvantage**: only half of the available capacity is usable



Redundant Array of Inexpensive Disks (**RAID**)

HW, SW

- **Hardware** implementation:
  - Use of RAID controllers
  - Manage system independently of OS
  - Offload I/O operation and parity computation
  - Cost usually high
- **Software** implementation:
  - OS used to manage RAID configuration
  - Impact on CPU usage can be high
- **Disadvantage**: scaling to multiple servers is not possible

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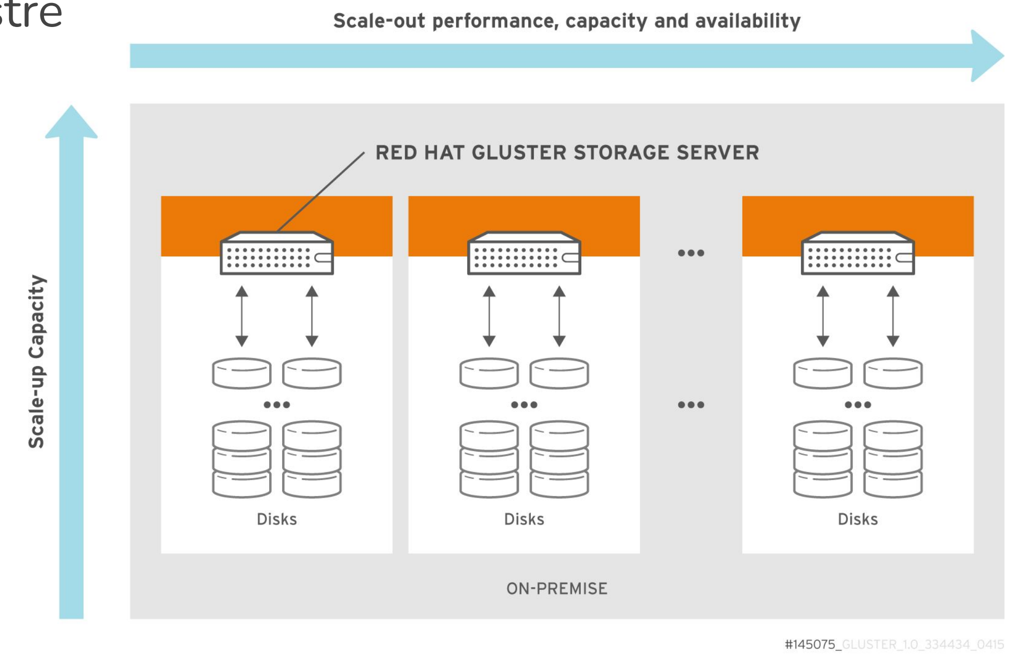
Distributed storage systems

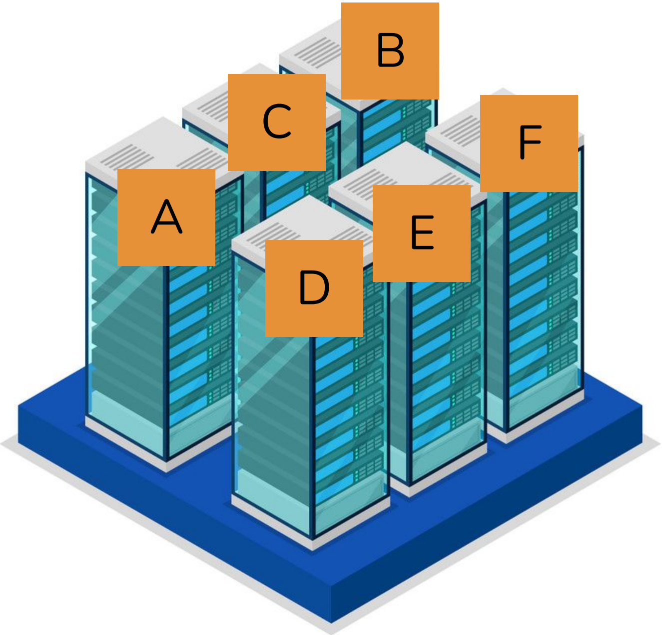
Distributed storage systems

- **Distributed storage system**: files are shared and distributed between multiple nodes
  - Active communities (Red Hat, IBM, Apache, Intel)
  - Example: Ceph, Gluster, Hadoop, Lustre
  - Used by some experiments (CMS)
  - Interesting features:
    - load balancing
    - data replication
    - smart placement policies
    - scaling up to O(1000) nodes



Distributed storage systems in DAQ

- **Application in DAQ**: implementation of the **event builder**:
    - **Physical event building** (**traditional approach**): data fragments are fetched explicitly over a network from temporary buffers at the readout nodes to a single physical location



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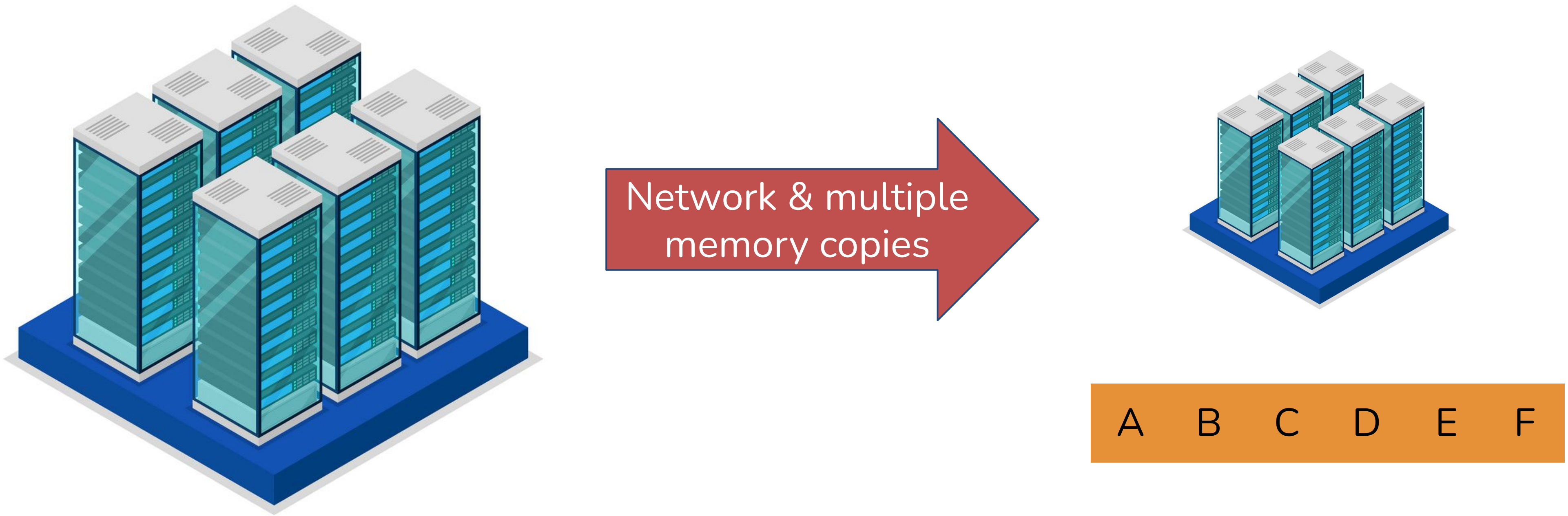

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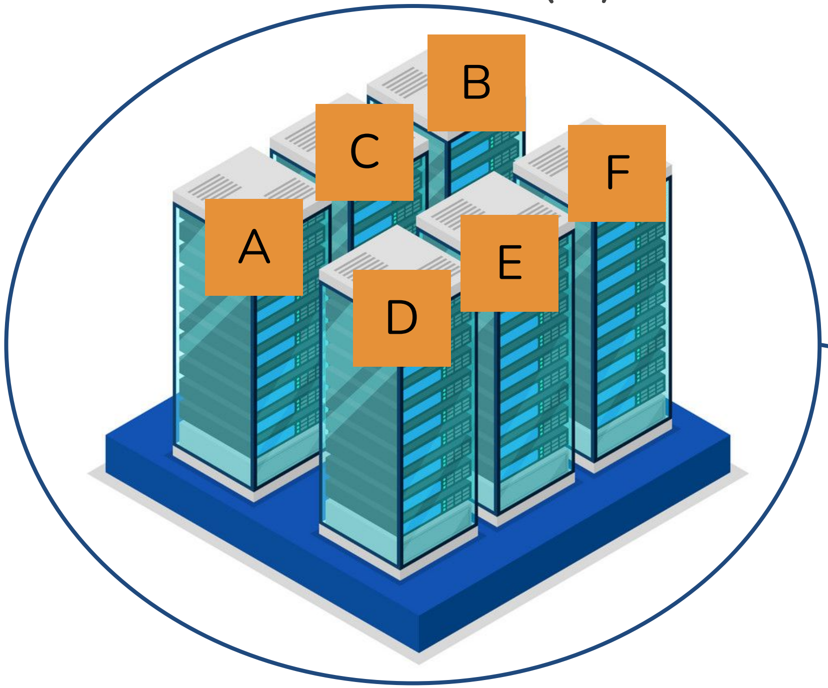
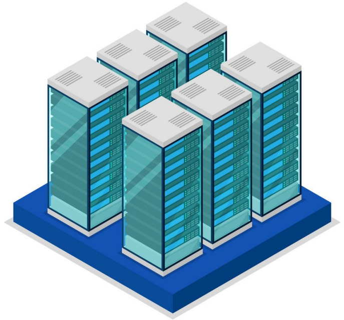
- **Application in DAQ**: implementation of the **event builder**:
  - **Logical event building**: fragments are stored in a large distributed system and events are built by computing the location of the fragments (metadata operation)
- **R&D** for future DAQ systems: ATLAS (Phase-II), DUNE, etc.





Example: Intel DAOS
(Distributed Asynchronous Object Store)

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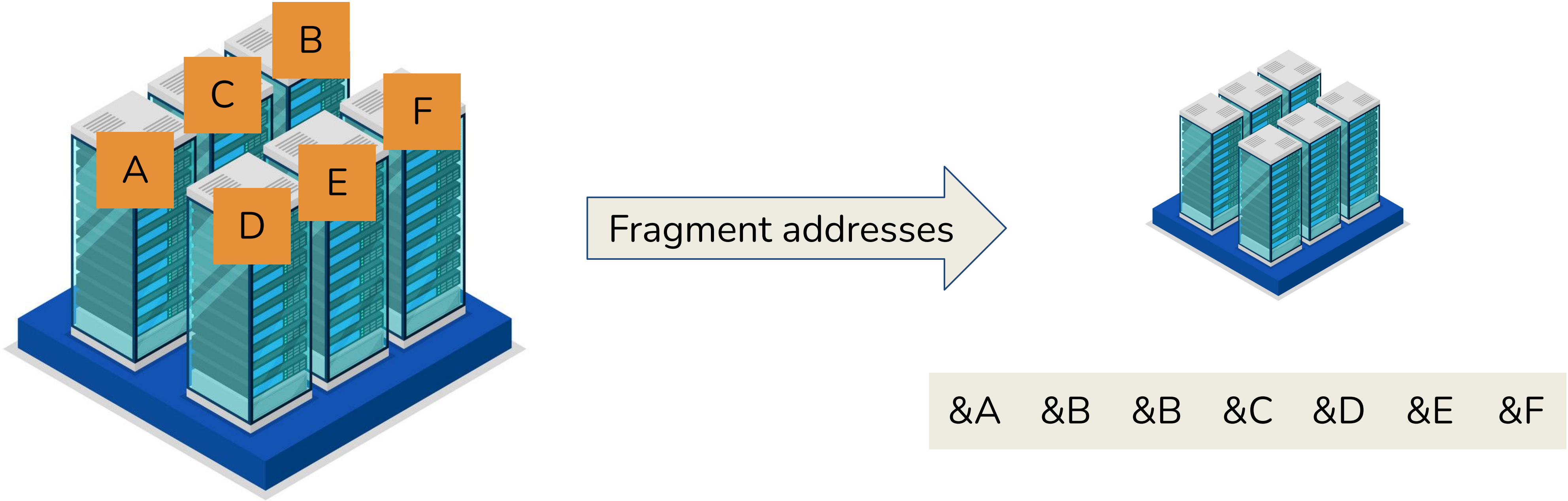


DAQ takeaway
Storage technologies

- Different storage media available on the market for different use cases
  - Long term storage, mostly sequential access → HDD
  - Low latency and large capacity → SSD
  - High rate and persistent → Non-Volatile memory
  - Fast and temporary → DRAM
- Keep in mind that **price/GB** changes a lot for different storage media
- When designing a DAQ system always keep an eye on the target throughput and required latency for your application
- **Data safety** and **reliability** is an important factor!
  - RAID and Distributed systems

Storage challenges for the next generation DAQ systems

- Physics signals are rare!
  - Higher intensity beams are needed
  - More granular detectors
  - Consequence: more data to store

- HL-LHC: Data rates and data bandwidths will increase by ~ 1 order of magnitude
  - Consequence: scale up DAQ systems
  - Use commercial off-the-shelf technology as much as possible

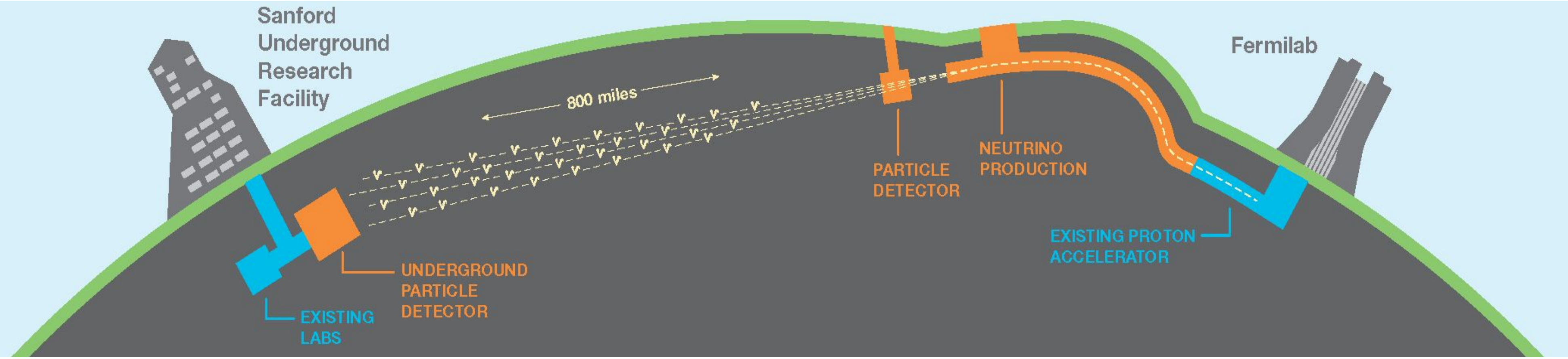
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Storage systems in HEP

Source: CDS

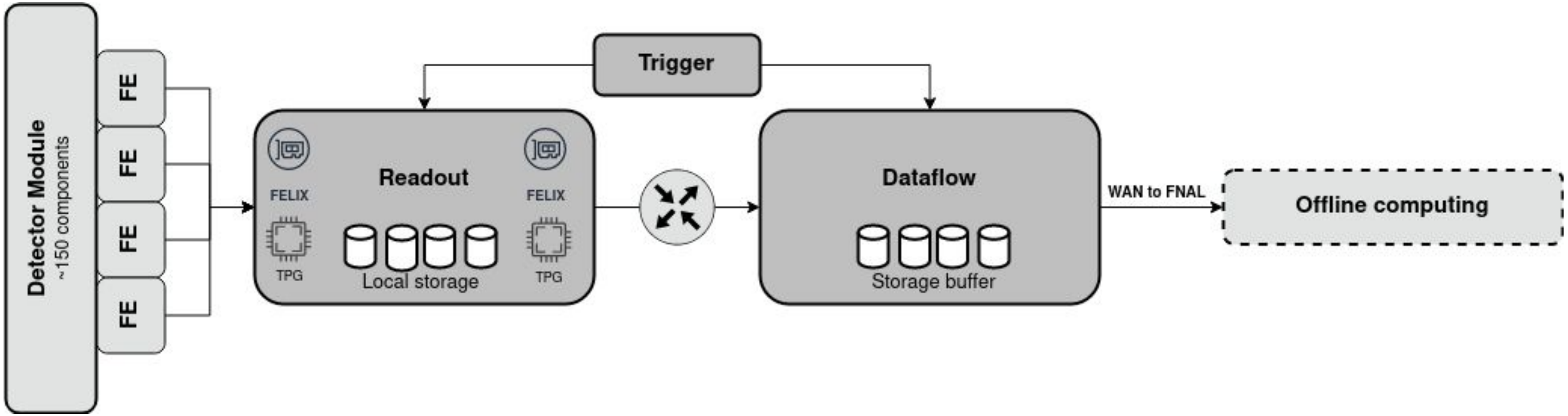
DUNE experiment
Quick overview

- Neutrino experiment located at Sanford Underground Research Facility in South Dakota
- Far detector located 1300 km away from source and approximately 1.5 km underground
- 4 modules of 17 kton LAr time projection chamber
    - Each module can be split in ~150 identical components
- Prototypes available at CERN in the North Area (ProtoDUNE)



DUNE Data AcQuisition system (DAQ)

- Modular nature of the apparatus allows splitting a cryostat in ~150 identical components



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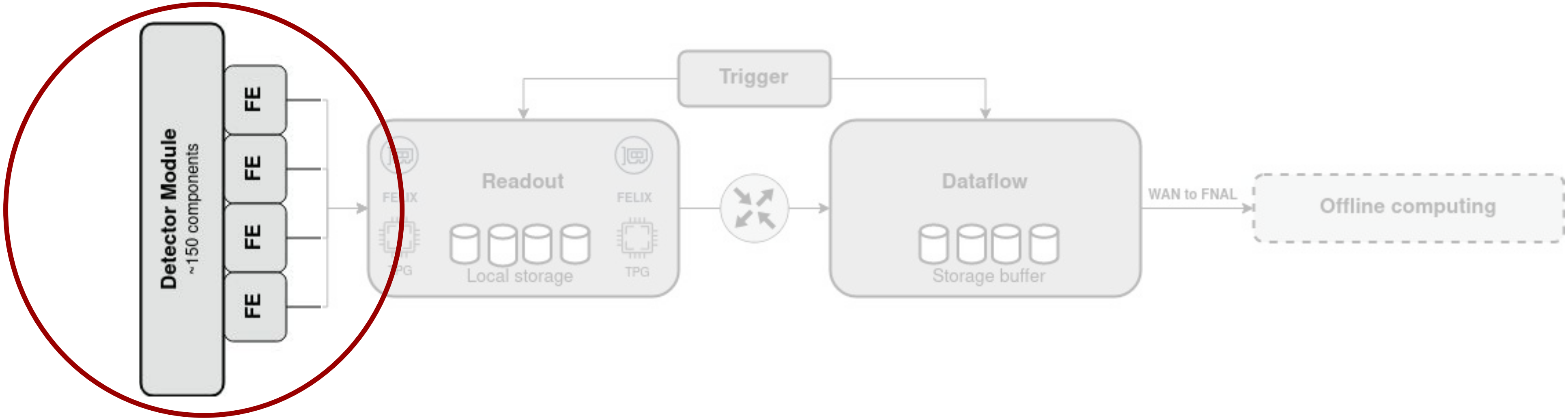

DUNE uses a continuous readout for the LArTPC

- 2 MHz sampling rate, 384k channels, 14 bit ADC
  - Throughput: ~**1.5 TB/s**
- Adding up all the TDAQ from the four cryostats leads to ~**6 TB/s** = 1000 movies in 4K per second
  - Similar rate expected for HL-LHC experiments !

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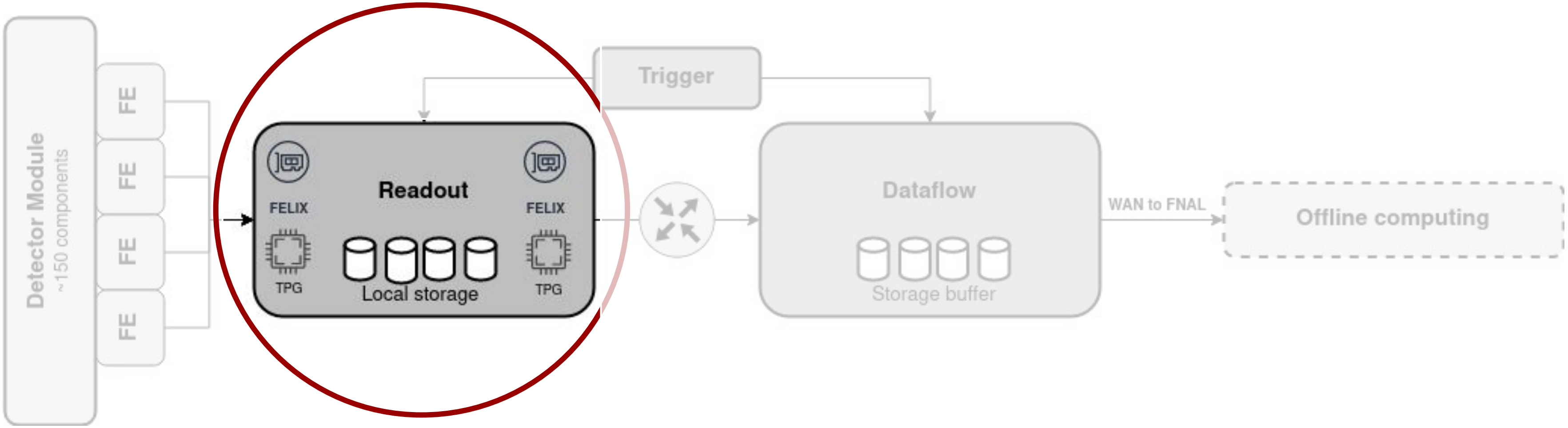
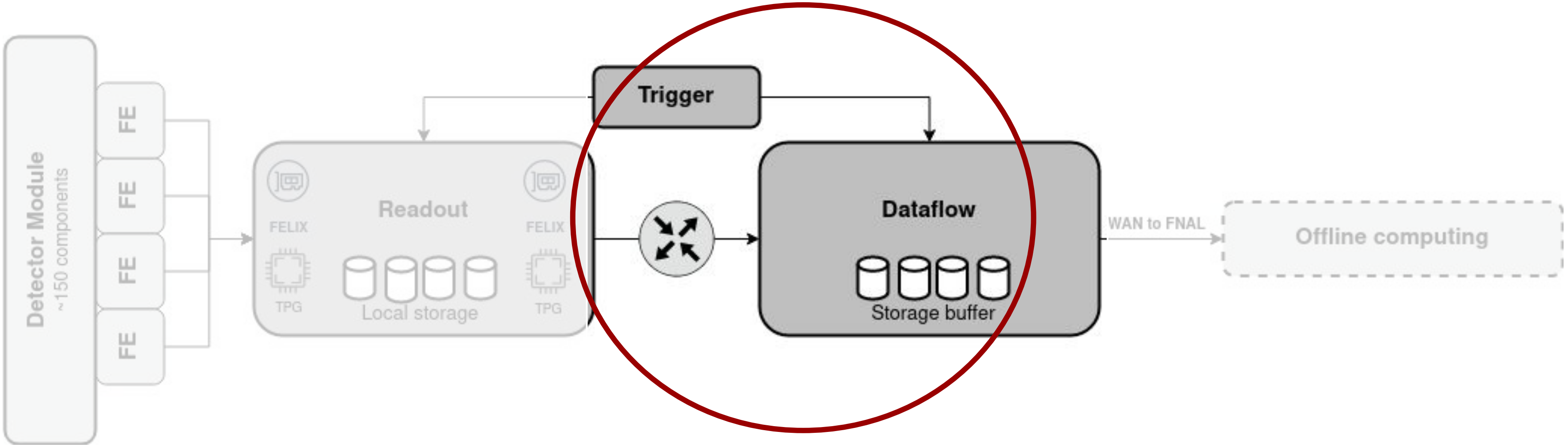


Readout system interfaces the detector front-end with the DAQ processing units

- Commercial-off-the-shelf server with multiple uses:
  - Detector interface: handle the data input from the front-end electronics of the detector
  - Low-level data selection system (*Trigger Primitive Generation*): identify time periods with signal
  - **Local storage buffer**: temporary store the data while waiting for a trigger decision
- **Data throughput** for each readout unit: approximately **10 GB/s**
  - 150 identical readout units —> total of **~1.5 TB/s** for each cryostat

DUNE Data AcQuisition system (DAQ)

- Modular nature of the apparatus allows splitting a cryostat in ~150 identical components



Trigger combines a subset of readout (TPs) data into time windows of interesting signals:

- Time “window” can vary from **< 1 ms** to ~**100 s**;
- Data size ranging from few MB to ~150 TB

Dataflow moves the data fragments (identified by the trigger) from the Readout nodes to a large storage buffer

- Total storage size is **1 PB** (approximately one week of data taking) = 150k movies in 4K

DUNE Data AcQuisition system (DAQ)

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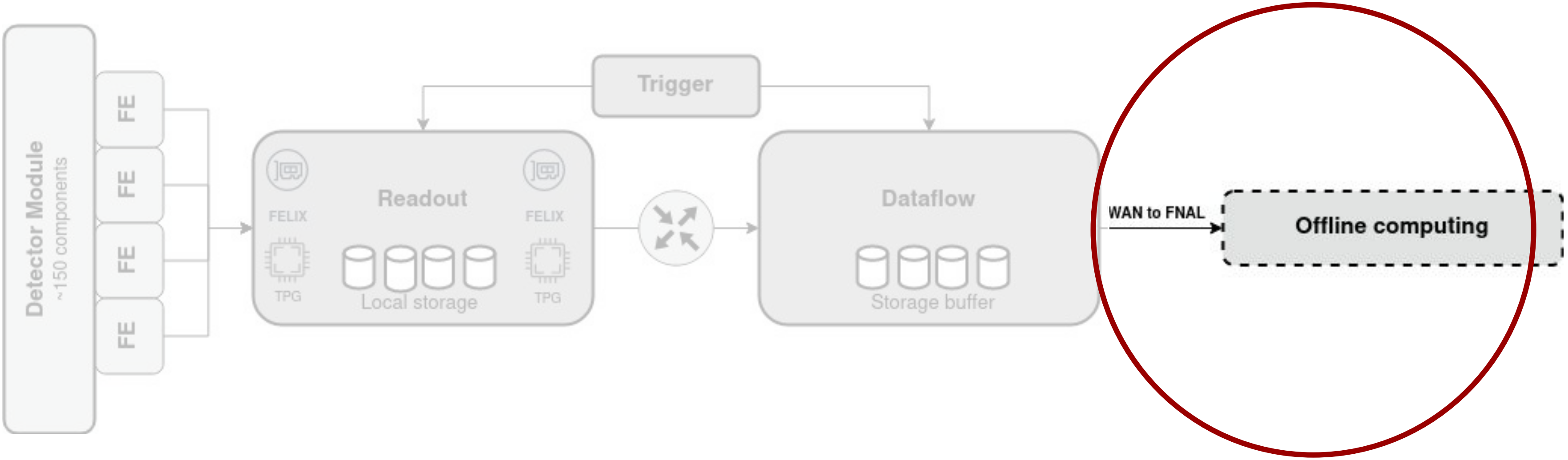


Transfer recorded data to Fermilab computing infrastructure

- Total transfer of **~30 PB/year** (across all detector modules)

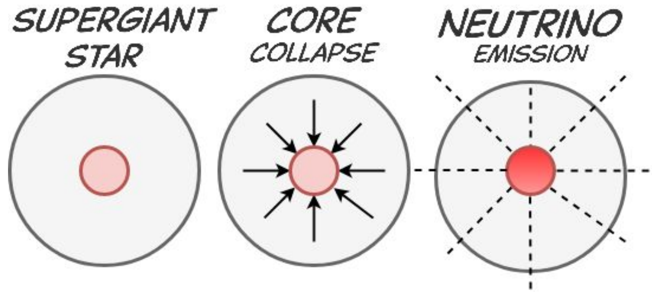
Physics constraints on the DUNE DAQ

The physics goals of the DUNE experiment heavily drive the DAQ design

- Wide physics program results in the study of many **different types of events**
  - Support data taking over a wide energy spectrum
    - Trigger system will need both a self-triggering mechanism for the many low-energy deposits as well as a triggering system for the high energy (> 100 MeV) interactions
    - DAQ must support a **very wide range of readout windows**
      - Data size can vary several orders of magnitude (from MB to TB)

Storage system and buffering becomes crucial to support all data taking operations

Supernova Neutrino Burst



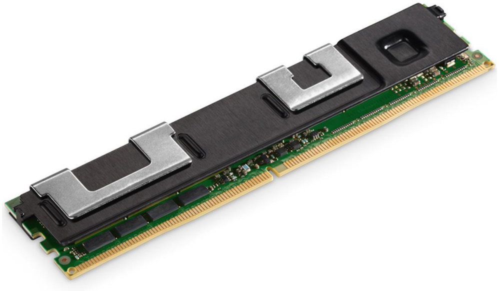
- **Supernova Neutrino Burst** (SNB) detection
  - One of the physics goals of DUNE
  - Detection of **rare** and **low energy** event
- Data taking of SNB events is **complex**:
  - Long trigger latency
  - Physics event distributed over time
  - **Critical data**: avoid any potential loss
- **Requirements**:
  - A single detector module generates O(10) GB/s
  - On supernova trigger: **persist O(100) seconds** (i.e. 150 TB per cryostat)

Supernova Neutrino buffer

Persistent memory

- Critical data and high bandwidth:
    - Take advantage of storage adapters
        - Connect multiple SSD drives together: up to 4 x PCIe 4.0 devices
    - Use of Non-Volatile Memory technology (3D XPoint)

- **Successful prototypes** capable of buffering data from the readout system
    - Store for over 100 seconds
    - Sustained target throughput of 10 GB/s



- Successfully tested and integrated the devices within the DUNE DAQ

Conclusions

- Storage system is crucial for physics results
- Online data taking has different requirements from offline analysis
- Design of a storage system:
    - Focus on **throughput** to support the system
    - **Latency** constraints
    - Access pattern
    - Several **storage media** for different use-cases (HDD, SSD, NVM, DRAM)
    - Take into account redundancy and **fault tolerance**
- Benchmark performance of devices. Tools: DD and FIO (and many others)

Thank you ! Questions ?

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