Chapter 12: Physical Storage Systems

Brief overview of Physical Storage Media for Databases, to be aware of its incidence on the design of DBMSs

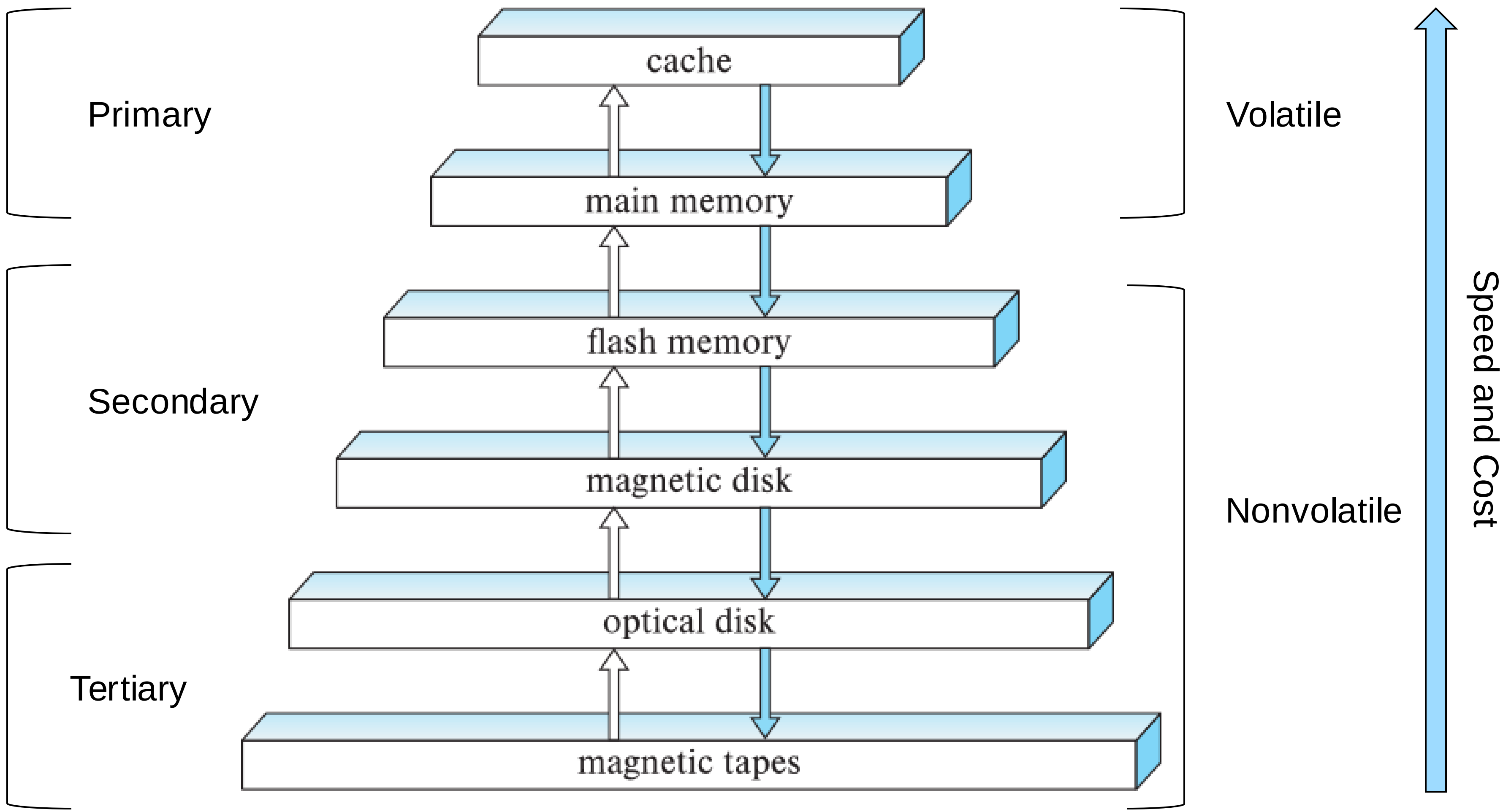
Sistemas de Bases de Dados 2024/25

Capítulo refere-se a: Database System Concepts, 7th Ed

Classification of Physical Storage Media

- In the end, a database must be physically stored in computer(s)
- Storage can be differentiated into:
  - **volatile storage:** loses contents when power is switched off
  - **non-volatile storage**:
    - Contents persist even when power is switched off.
    - Includes secondary and tertiary storage, as well as battery-backed up main-memory.
- Factors affecting choice of storage media include:
  - Speed with which data can be accessed
  - Cost per unit of data
  - Reliability

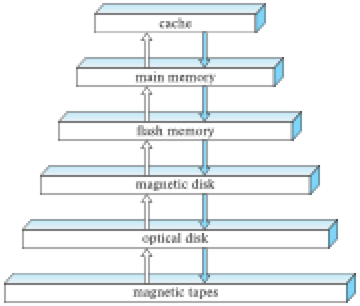
Storage Hierarchy



Storage Hierarchy (Cont.)

- **primary storage:** Fastest media but volatile (cache, main memory).
- **secondary storage:** next level in hierarchy, non-volatile, moderately fast access time
  - Also called **on-line storage**
  - E.g., flash memory, magnetic disks
- **tertiary storage:** lowest level in hierarchy, non-volatile, slow access time
  - also called **off-line storage** and used for **archival storage**
  - e.g., magnetic tape, optical storage
  - Magnetic tape
    - Sequential access, 1 to 12 TB capacity
    - A few drives with many tapes
    - Juke boxes with petabytes (1000's of TB) of storage

Storage Hierarchy (Cont.)



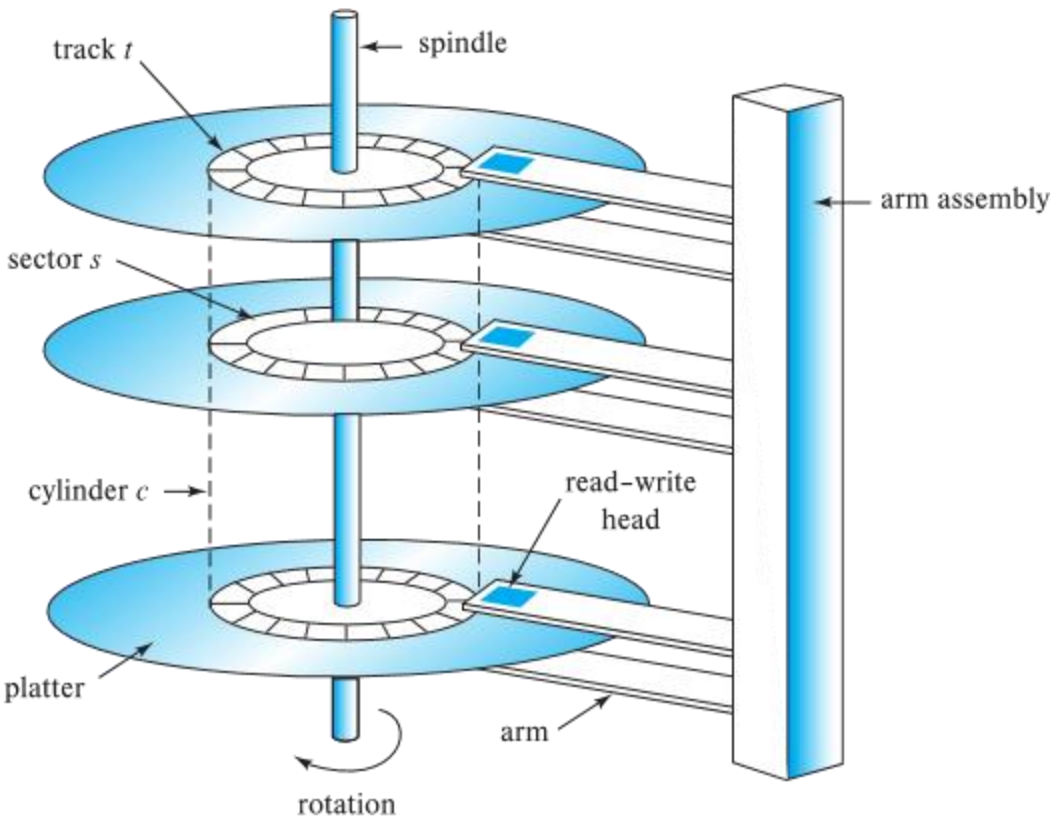
- **Cache and Main Memory**
  - Fast access (10s to 100s of nanoseconds)
  - Generally, too small (or expensive) to store the entire database
  - **Volatile**
- **Flash memory**
  - Non-volatile fast read-access memory
  - Write is not as fast – and requires prior erasure
  - Limited number of erasures
  - Not yet with enough capacity or competitive price to be considered for really big databases
- **Magnetic disks**
  - Still the medium of choice for database storage
  - Data moved to main memory for access, and written back to disk
  - Reliable
- **Optical disks and Tapes**
  - Mainly used for backups (off-line/archival storage)
  - Slow access time

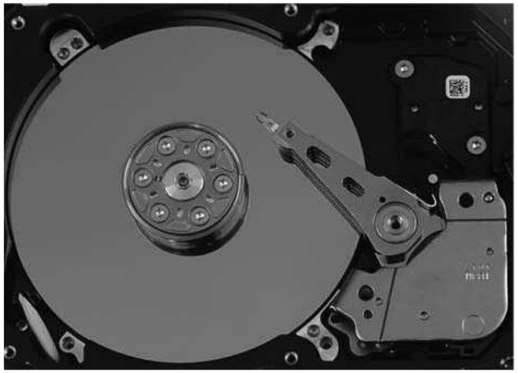
Storage Interfaces

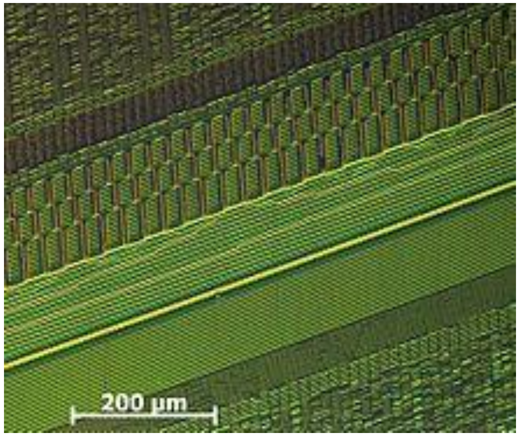
- Disk interface standards families
  - SATA (Serial ATA)
    - SATA 3 supports data transfer speeds of up to 6 gigabits/sec
  - SAS (Serial Attached SCSI)
    - SAS Version 3 supports 12 gigabits/sec
  - NVMe (Non-Volatile Memory Express) interface
    - Works with PCIe connectors to support lower latency and higher transfer rates
    - Supports data transfer rates of up to 24 gigabits/sec
- Disks usually connected directly to computer system
- In **Storage Area Networks (SAN)**, a large number of disks are connected by a high-speed network to a number of servers
- In **Network Attached Storage (NAS)** networked storage provides a file system interface using networked file system protocol, instead of providing a disk system interface

Magnetic Hard Disk Mechanism

- It is worth looking at how magnetic disks work
  - After all they are the place where most databases are stored!

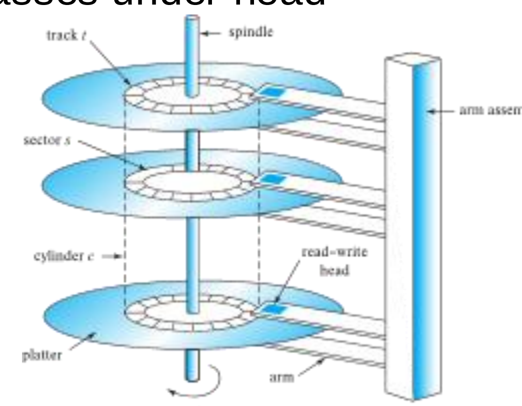






Magnetic Disks

- **Read-write head**
  - Very close to platter surface, reads and writes magnetically encoded info
- Surface of platter divided into circular **tracks**
  - Over 50K-100K tracks per platter on typical hard disks
- Each track is divided into **sectors.**
  - A sector is the smallest unit of data that can be read or written.
  - Sector size is typically 512 bytes
  - Typical sectors per track: 500 to 1000 (on inner tracks) to 1000 to 2000 (on outer tracks)
- To read/write a sector
  - disk arm swings to position head on right track
  - platter spins continually; data is read/written as sector passes under head
- Head-disk assemblies
  - multiple disk platters on a single spindle (1 to 5 usually)
  - one head per platter, mounted on a common arm.
- **Cylinder** *i* consists of i^{th} track of all the platters



Magnetic Disks (Cont.)

- **Disk controller** – interfaces between the computer system and the disk drive hardware.
  - accepts high-level commands to read or write a sector
  - initiates actions such as moving the disk arm to the right track and actually reading or writing the data
  - Computes and attaches **checksums** to each sector to verify that data is read back correctly
    - If data is corrupted, with very high probability stored checksum won't match recomputed checksum
  - Ensures successful writing by reading back sector after writing it
  - Performs **remapping of bad sectors**

Performance Measures of Disks

- **Access time** – the time it takes from when a read or write request is issued to when data transfer begins. Consists of:
  - **Seek time** – time it takes to reposition the arm over the correct track.
    - Average seek time is 1/2 the worst case seek time.
    - 4 to 10 milliseconds on typical disks
  - **Rotational latency** – time it takes for the sector to be accessed to appear under the head.
    - 4 to 11 milliseconds on typical disks (5400 to 15000 r.p.m.)
    - Average latency is 1/2 of the above latency.
  - Overall latency is 5 to 20 msec depending on disk model
- **Data-transfer rate** – the rate at which data can be retrieved from or stored to the disk.
  - 25 to 200 MB per second max rate, lower for inner tracks

Performance Measures (Cont.)

- **Disk block** is a logical unit for storage allocation and retrieval
  - 4 to 16 kilobytes typically
    - Smaller blocks: more transfers from disk
    - Larger blocks: more space wasted due to partially filled blocks
- **Sequential access pattern**
  - Successive requests are for successive disk blocks
  - Disk seek required only for first block
  - (if the blocks are stored successively in the disk)
- **Random access pattern**
  - Successive requests are for blocks that can be anywhere on disk
  - Each access requires a seek
  - Transfer rates are low since a lot of time is wasted in seeks
- **I/O operations per second (IOPS)**
  - Number of random block reads that a disk can support per second
  - 50 to 200 IOPS on current generation magnetic disks

Performance Measures (Cont.)

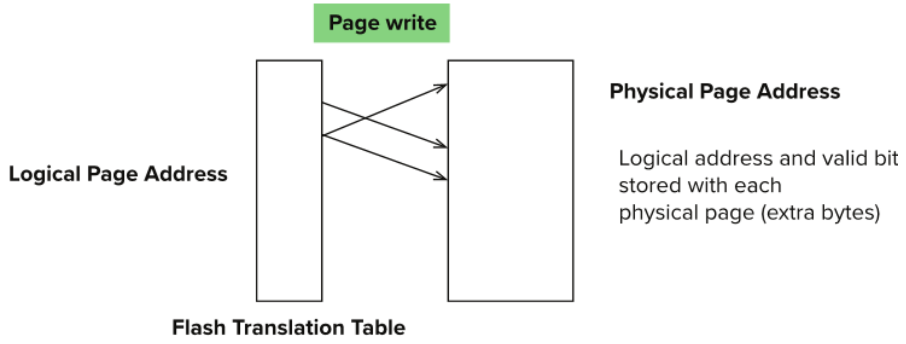
- **Mean time to failure (MTTF)** – the average time the disk is expected to run continuously without any failure.
  - Typically 3 to 5 years
  - Probability of failure of new disks is quite low, corresponding to a "theoretical MTTF" of 500,000 to 1,200,000 hours for a new disk
    - E.g., an MTTF of 1,200,000 hours for a new disk means that given 1000 relatively new disks, on an average one will fail every 1200 hours
  - MTTF decreases as disk ages

Flash Storage

- NOR flash vs NAND flash
- NAND flash
  - used widely for storage, cheaper than NOR flash
  - requires page-at-a-time read (page: 512 bytes to 4 KB)
    - 20 to 100 microseconds for a page read
    - Not much difference between sequential and random read
  - Page can only be written once
    - Must be erased to allow rewrite
- **Solid state disks**
  - Use standard block-oriented disk interfaces, but store data on multiple flash storage devices internally
  - Transfer rate of up to 500 MB/sec using SATA, and up to 3 GB/sec using NVMe PCIe

Flash Storage (Cont.)

- Erase happens in units of **erase block**
  - Takes 2 to 5 millisecs
  - Erase block typically 256 KB to 1 MB (128 to 256 pages)
- **Remapping** of logical page addresses to physical page addresses avoids waiting for erase
- **Flash translation table** tracks mapping
  - also stored in a label field of flash page
  - remapping carried out by **flash translation layer**



- After 100,000 to 1,000,000 erases, erase block becomes unreliable and cannot be used

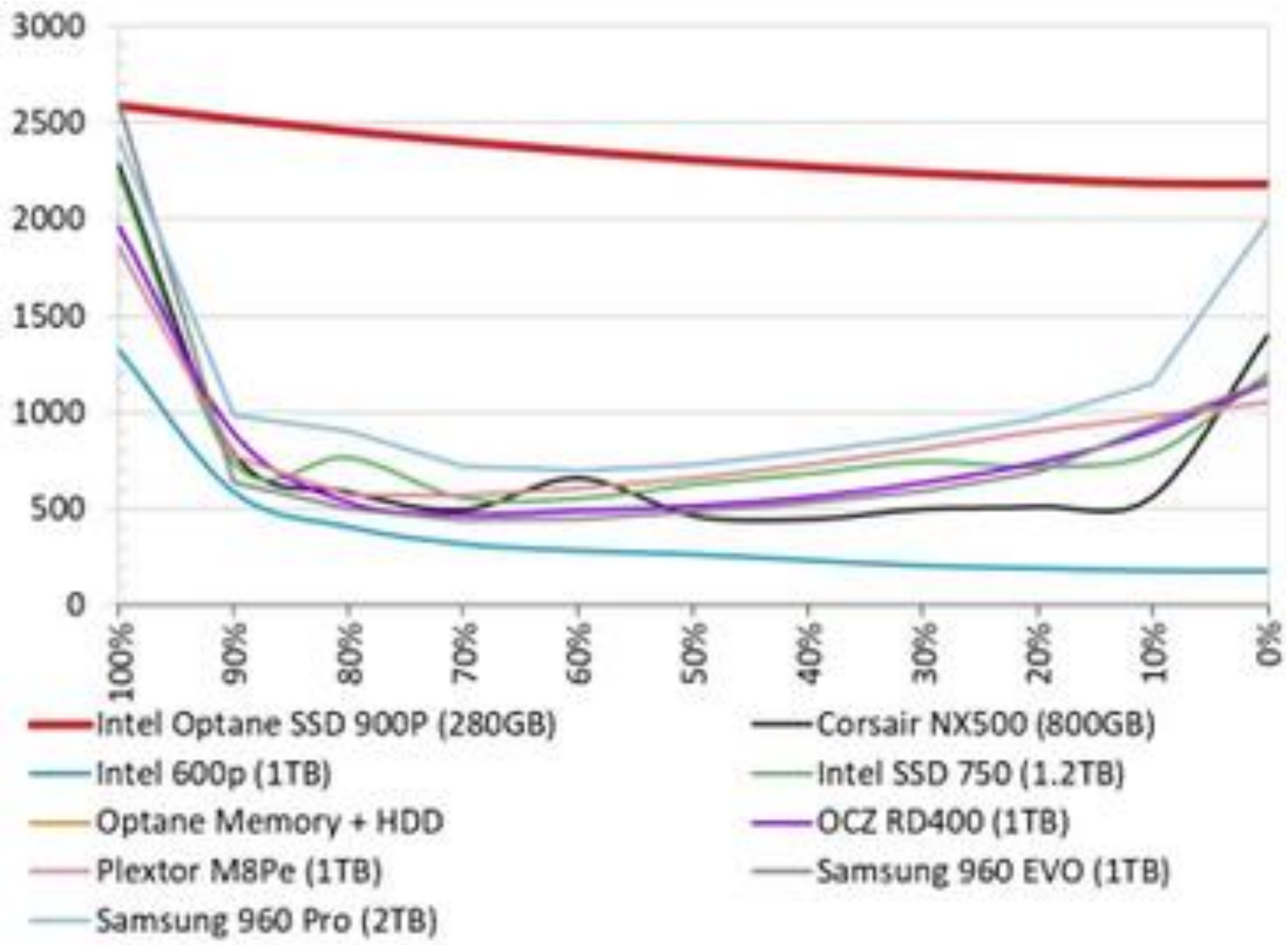
SSD Performance Metrics

- Random reads/writes per second
  - Typical 4KB reads: 10,000 reads per second (10,000 IOPS)
  - Typical 4KB writes: 40,000 IOPS
  - SSDs support parallel reads
    - Typical 4KB reads:
      - 100,000 IOPS with 32 requests in parallel (QD-32) on SATA
      - 350,000 IOPS with QD-32 on NVMe PCIe
    - Typical 4KB writes:
      - 100,000 IOPS with QD-32, even higher on some models
- Data transfer rate for sequential reads/writes
  - 400 MB/sec for SATA3, 2 to 3 GB/sec using NVMe PCIe
- **Hybrid disks**: combine small amount of flash cache with larger magnetic disk

3D-XPoint

- Discontinued... But it was good!

Throughput MB/s

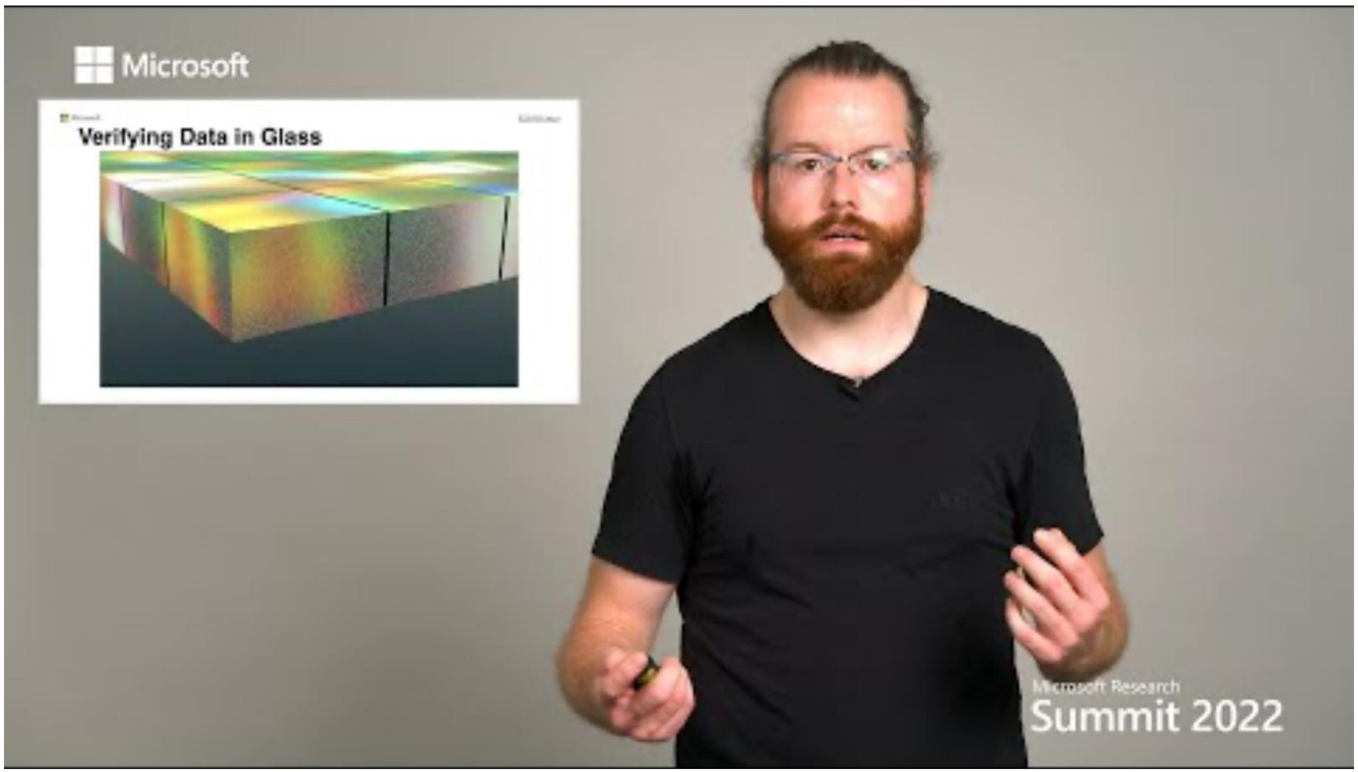


Mix of read-write

https://en.wikipedia.org/wiki/3D_XPoint

Project Silica

- Store data in glass using lasers
  - 7TB of capacity in the size of a DVD
  - Store data for thousands of years



RAID

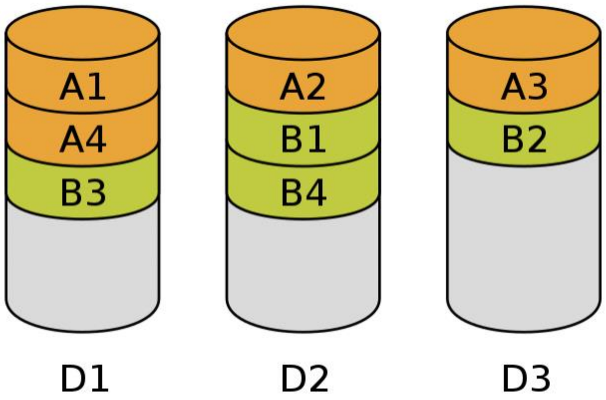
- **RAID: Redundant Arrays of Independent Disks**
  - disk organization techniques that manage a large numbers of disks, providing a view of a single disk of
    - **high capacity** and **high speed** by using multiple disks in parallel,
    - **high reliability** by storing data redundantly, so that data can be recovered even if a disk fails
- The chance that some disk out of a set of *N* disks will fail is much higher than the chance that a specific single disk will fail.
  - E.g., a system with 100 disks, each with MTTF of 100,000 hours (approx. 11 years), will have a system MTTF of 1000 hours (approx. 41 days)
  - Techniques for using redundancy to avoid data loss are critical with large numbers of disks

Improvement of Reliability via Redundancy

- **Redundancy** – store extra information that can be used to rebuild information lost in a disk failure
- E.g., **Mirroring** (or **shadowing**)
  - Duplicate every disk. Logical disk consists of two physical disks.
  - Every write is carried out on both disks
    - Reads can take place from either disk
  - If one disk in a pair fails, data still available in the other
    - Data loss would occur only if a disk fails, and its mirror disk also fails before the system is repaired
      - Probability of combined event is very small
        - Except for dependent failure modes such as fire or building collapse or electrical power surges
- **Mean time to data loss** depends on mean time to failure, and **mean time to repair**
  - E.g., MTTF of 100,000 hours, mean time to repair of 10 hours gives mean time to data loss of $500*10^6$ hours (or 57,000 years) for a mirrored pair of disks (ignoring dependent failure modes)

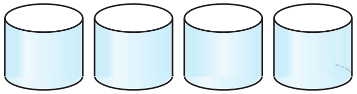
Improvement in Performance via Parallelism

- Two main goals of parallelism in a disk system:
  1. Load balance multiple small accesses to increase throughput
  2. Parallelize large accesses to reduce response time.
- Improve transfer rate by striping data across multiple disks.
- **Block-level striping** – with *n* disks, block *i* of a file goes to disk (*i* mod *n*) + 1
  - Requests for different blocks can run in parallel if the blocks reside on different disks
  - A request for a long sequence of blocks can utilize all disks in parallel
- **Bit-level striping** – split the bits of each byte across multiple disks (not used much anymore)
  - In an array of eight disks, write bit *i* of each byte to disk *i.*
  - Each access can read data at eight times the rate of a single disk.
  - But seek/access time worse than for a single disk
  - Not used anymore

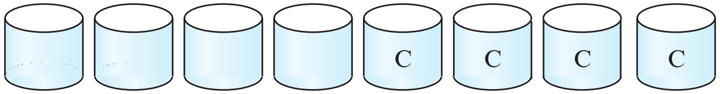


RAID Levels

- Schemes to provide redundancy at lower cost by using disk striping combined with parity bits
  - Different RAID organizations, or RAID levels, have differing cost, performance and reliability characteristics
- **RAID Level 0**: Block striping; non-redundant.
  - Used in high-performance applications where data loss is not critical.
- **RAID Level 1**: Mirrored disks with block striping
  - Offers best write performance.
  - Popular for applications such as storing log files in a database system.



(a) RAID 0: nonredundant striping



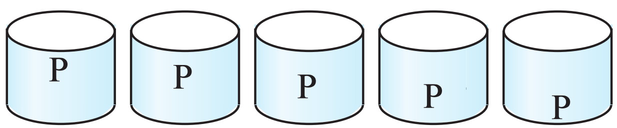
(b) RAID 1: mirrored disks

RAID Levels (Cont.)

- **Parity blocks**: Parity block *j* stores XOR of bits from block *j* of each disk
  - When writing data to a block *j*, parity block *j* must also be computed and written to disk
    - Can be done by using old parity block, old value of current block and new value of current block (2 block reads + 2 block writes)
    - Or by recomputing the parity value using the new values of blocks corresponding to the parity block
      - More efficient for writing large amounts of data sequentially since the parity blocks can be computed from the sequence being written
  - To recover data for a block, compute XOR of bits from all other blocks in the set including the parity block

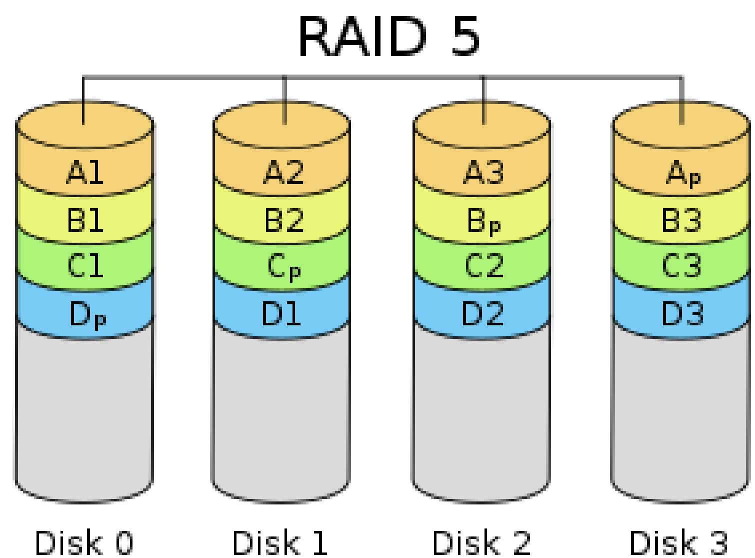
RAID Levels (Cont.)

- **RAID Level 5:** Block-Interleaved Distributed Parity; partitions data and parity among all *N* + 1 disks, rather than storing data in *N* disks and parity in 1 disk.
  - E.g., with 5 disks, parity block for *n*th set of blocks is stored on disk (*n mod* 5) + 1, with the data blocks stored on the other 4 disks.



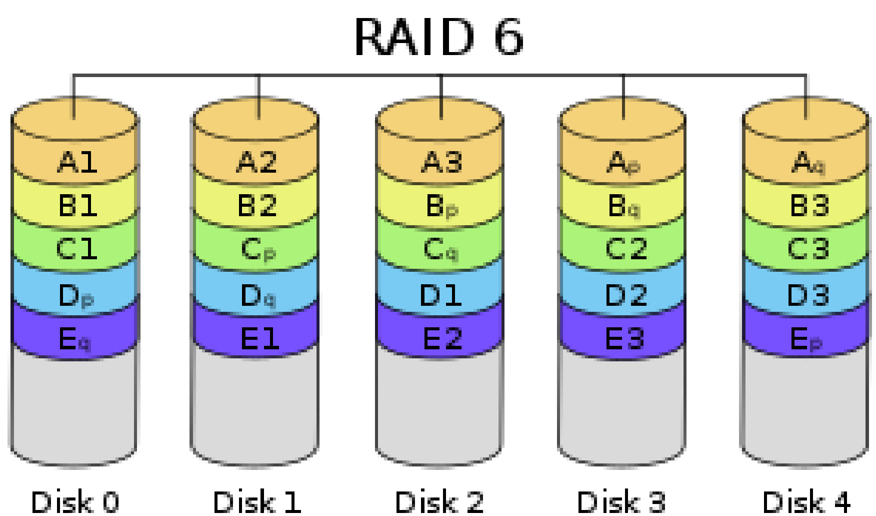
(c) RAID 5: block-interleaved distributed parity

P0	0	1	2	3
4	P1	5	6	7
8	9	P2	10	11
12	13	14	P3	15
16	17	18	19	P4



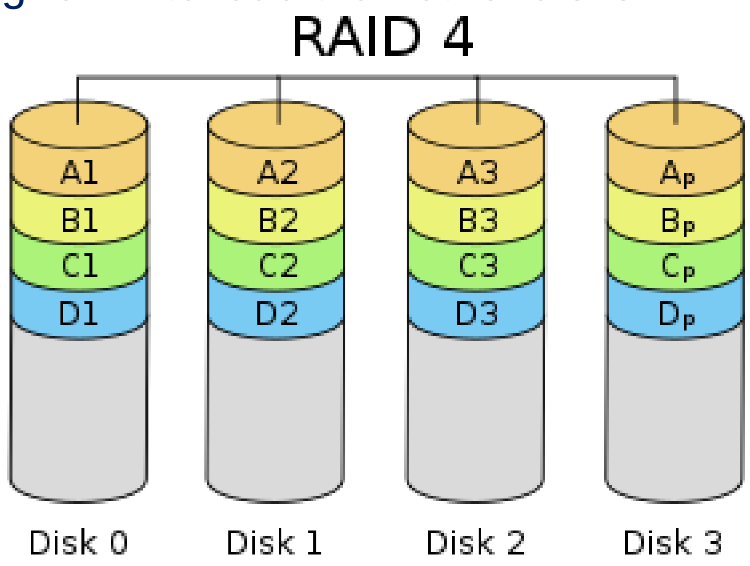
RAID Levels (Cont.)

- **RAID Level 5** (Cont.)
  - Block writes occur in parallel if the blocks and their parity blocks are on different disks.
- **RAID Level 6**: P+Q Redundancy scheme; similar to Level 5, but stores two error correction blocks (P, Q) instead of single parity block to guard against multiple disk failures.
  - Better reliability than Level 5 at a higher cost
    - Becoming more important as storage sizes increase



RAID Levels (Cont.)

- **Other levels (not used in practice):**
  - **RAID Level 2**: Memory-Style Error-Correcting-Codes (ECC) with bit striping.
  - **RAID Level 3**: Bit-Interleaved Parity
  - **RAID Level 4:** Block-Interleaved Parity; uses block-level striping, and keeps a parity block on a separate ***parity disk*** for corresponding blocks from *N* other disks.
    - RAID 5 is better than RAID 4, since with RAID 4 with random writes, parity disk gets much higher write load than other disks and becomes a bottleneck



Choice of RAID Level

- Factors in choosing RAID level
  - Monetary cost
  - Performance: Number of I/O operations per second, and bandwidth during normal operation
  - Performance during failure
  - Performance during rebuild of failed disk
    - Including time taken to rebuild failed disk
- RAID 0 is used only when data safety is not important
  - E.g., data can be recovered quickly from other sources

Choice of RAID Level (Cont.)

- Level 1 provides much better write performance than level 5
  - Level 5 requires at least 2 block reads and 2 block writes to write a single block, whereas Level 1 only requires 2 block writes
- Level 1 had higher storage cost than level 5
- Level 5 is preferred for applications where writes are sequential and large (many blocks), and need large amounts of data storage
- RAID 1 is preferred for applications with many random/small updates
- Level 6 gives better data protection than RAID 5 since it can tolerate two disk (or disk block) failures
  - Increasing in importance since latent block failures on one disk, coupled with a failure of another disk can result in data loss with RAID 1 and RAID 5.

Hardware Issues

- **Software RAID**: RAID implementations done entirely in software, with no special hardware support
- **Hardware RAID**: RAID implementations with special hardware
  - Use non-volatile RAM to record writes that are being executed
  - Beware: power failure during write can result in corrupted disk
    - E.g., failure after writing one block but before writing the second in a mirrored system
    - Such corrupted data must be detected when power is restored
      - Recovery from corruption is similar to recovery from failed disk
      - NV-RAM helps to efficiently detected potentially corrupted blocks
        - Otherwise all blocks of disk must be read and compared with mirror/parity block

To see the diferences...

Processador

AMD Epyc 7313 - 16c/32t - 3GHz/3.7GHz	

Memória

64GB DDR4 ECC 3200MHz	
128GB DDR4 ECC 3200MHz	+30,40 € + s/IVA/mês
256GB DDR4 ECC 3200MHz	+91,20 € + s/IVA/mês
512GB DDR4 ECC 3200MHz	+212,80 € + s/IVA/mês
1TB DDR4 ECC 2933MHz	+456,00 € + s/IVA/mês

Armazenamento

2× 4TB HDD SATA Soft RAID	
2× 960GB SSD NVMe Soft RAID	
2× 6TB HDD SATA Soft RAID	+25,08 € + s/IVA/mês
2× 960GB SSD NVMe + 2× 6TB HDD SATA Soft RAID	+31,35 € + s/IVA/mês
2× 1.92TB SSD NVMe Soft RAID	+49,40 € + s/IVA/mês
4× 960GB SSD NVMe Soft RAID	+49,40 € + s/IVA/mês
3× 1.92TB SSD NVMe Soft RAID	+74,10 € + s/IVA/mês
4× 6TB HDD SATA Hard RAID	+85,50 € + s/IVA/mês
4× 960GB SSD SATA Hard RAID	+85,50 € + s/IVA/mês
4× 1.92TB SSD NVMe Soft RAID	+98,80 € + s/IVA/mês
2× 3.84TB SSD NVMe Soft RAID	+98,80 € + s/IVA/mês
3× 3.84TB SSD NVMe Soft RAID	+148,20 € + s/IVA/mês
4× 3.84TB SSD NVMe Soft RAID	+197,60 € + s/IVA/mês

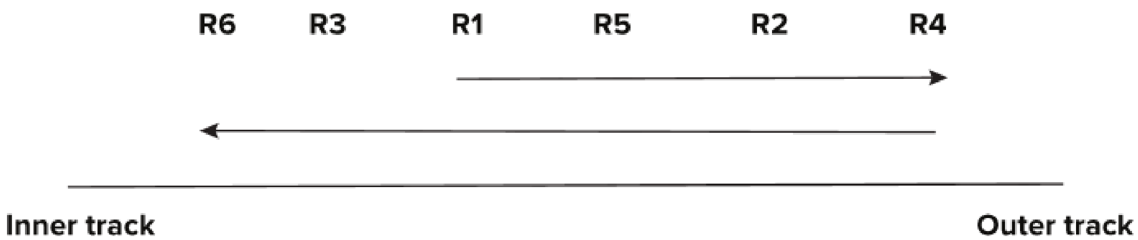
Base 192.84 €/month

Hardware Issues (Cont.)

- **Latent failures**: data successfully written earlier gets damaged
  - can result in data loss even if only one disk fails
- **Data scrubbing**:
  - continually scan for latent failures, and recover from copy/parity
- **Hot swapping**: replacement of disk while system is running, without power down
  - Supported by some hardware RAID systems,
  - reduces time to recovery, and improves availability greatly
- Many systems maintain spare disks which are kept online, and used as replacements for failed disks immediately on detection of failure
  - Reduces time to recovery greatly
- Many hardware RAID systems ensure that a single point of failure will not stop the functioning of the system by using
  - Redundant power supplies with battery backup
  - Multiple controllers and multiple interconnections to guard against controller/interconnection failures

Optimization of Disk-Block Access

- **Buffering:** in-memory buffer to cache disk blocks
- **Read-ahead:** Read extra blocks from a track in anticipation that they will be requested soon
- **Disk-arm-scheduling** algorithms re-order block requests so that disk arm movement is minimized
  - **elevator algorithm**



Optimization of Disk Block Access (Cont.)

- **File organization**
  - Allocate blocks of a file in as contiguous a manner as possible
  - Allocation in units of **extents** (sequences of contiguous blocks)
  - Files may get **fragmented**
    - E.g., if free blocks on disk are scattered, and newly created file has its blocks scattered over the disk
    - Sequential access to a fragmented file results in increased disk arm movement
    - Some systems have utilities to **defragment** the file system, in order to speed up file access
- **Non-volatile write buffers**
  - Some recovery algorithms require writing blocks by order, and so without non-volatile write buffers performance is substantially impacted.

End of Chapter 12