Chapter 12: Physical Storage Systems

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Classification of Physical Storage Media

- Can differentiate storage 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
- Factors affecting choice of storage media include
  - Speed with which data can be accessed
  - Cost per unit of data
  - Reliability

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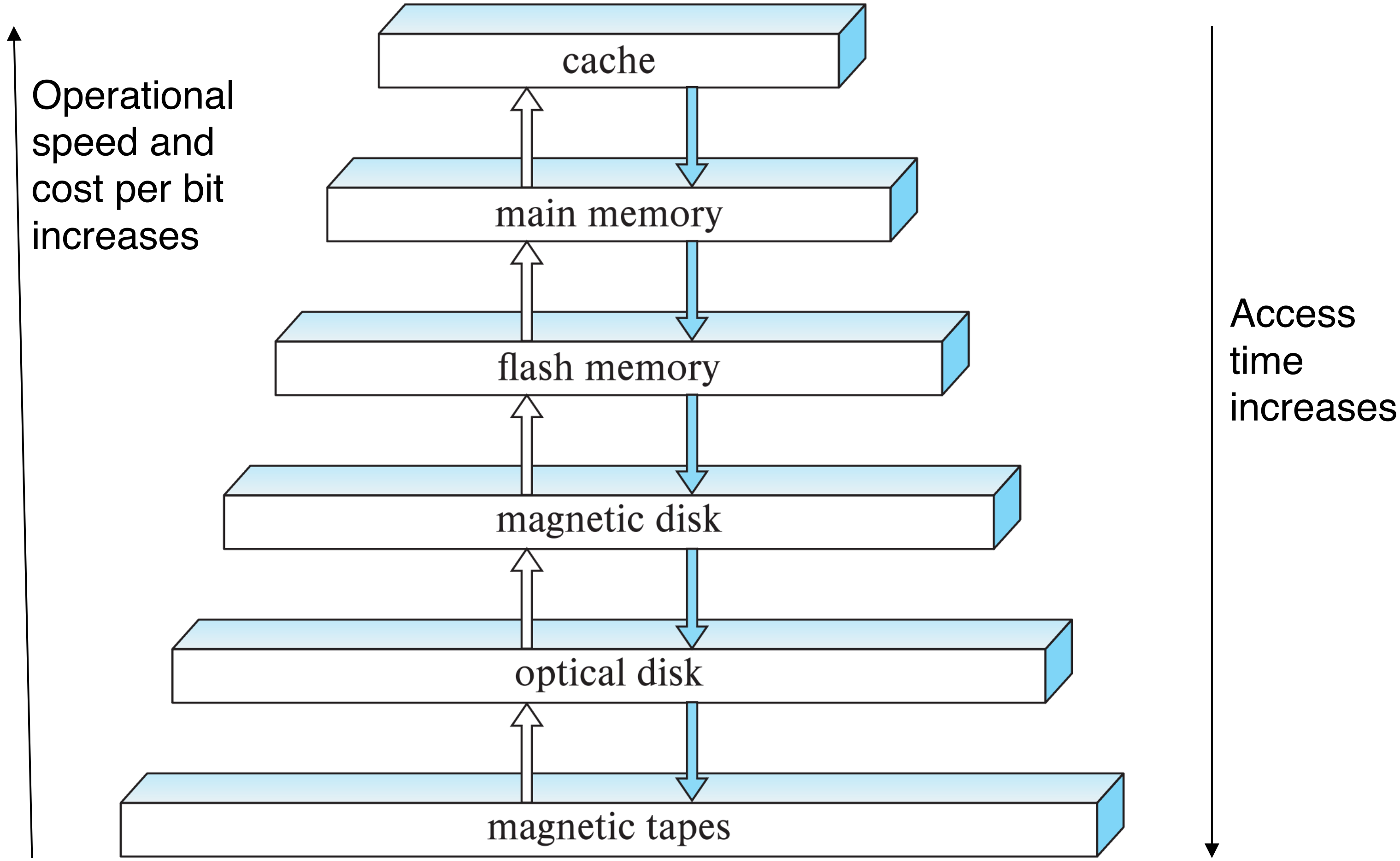
Storage Hierarchy



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

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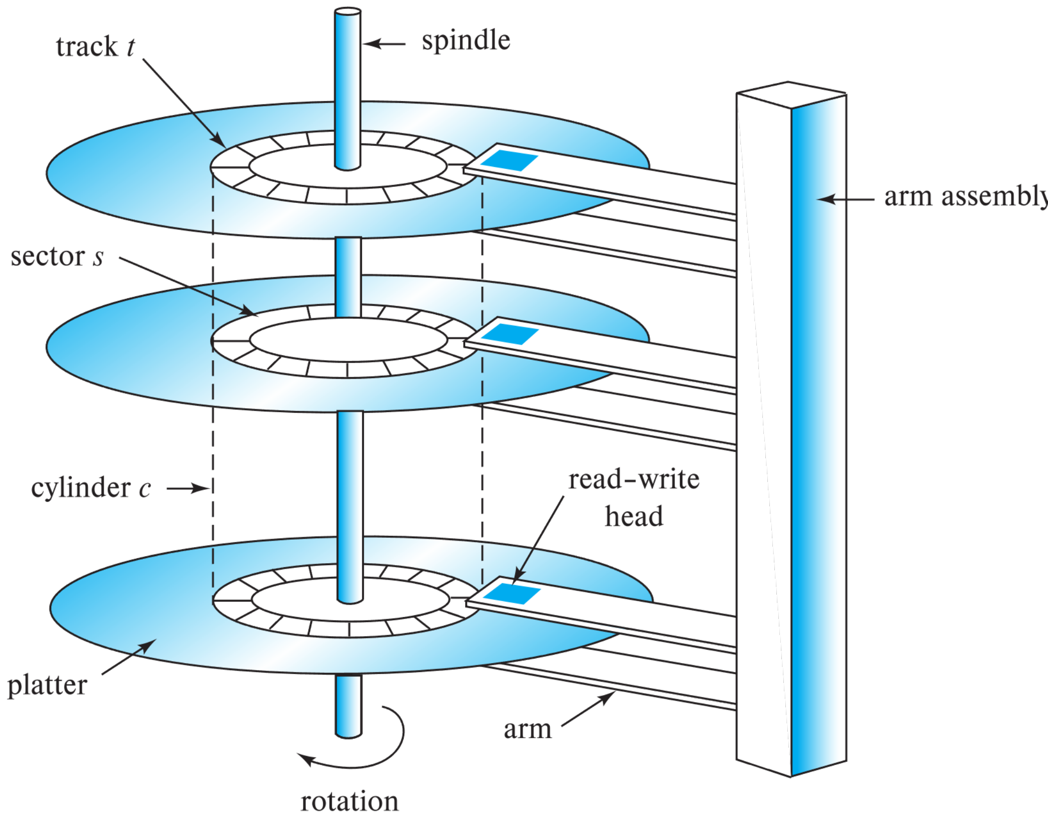
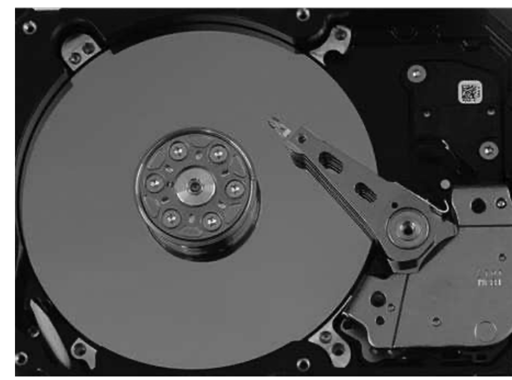
Storage Interfaces

- Disk interface standards families
  - SATA (Serial ATA(Advanced Technology Attachment)) used in PC and Servers
    - SATA 3 supports data transfer speeds of up to 6 gigabits/sec, allowing data transfer up to 600 megabytes per second.
  - SAS (Serial Attached SCSI (small computer system interface)) –only used in servers
    - SAS Version 3 supports 12 gigabits/sec,
  - NVMe (Non-Volatile Memory Express) interface used in SSD
    - 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





Schematic diagram of magnetic disk drive

Photo of magnetic disk drive

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Magnetic Disks

- **Read-write head**
- 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 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. Typically 2 to 20 milliseconds.
    - Average seek time is 1/2 the worst case(maximum) seek time.
      - Would be 1/3 if all tracks had the same number of sectors, and we ignore the time to start and stop arm movement
    - Average 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 full rotation of the disk.
  - 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.
  - 50 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 (disk $\Longleftrightarrow$ Main memory, called page)
  - 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
- **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

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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 (57 – 136 years) hours for a new disk
    - E.g., In practice if an MTTF of 1,200,000 hours for a new disk means that among the 1000 relatively new disks, on an average one of them will fail in 1200 hours
  - MTTF decreases as disk ages

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 one/some disks 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 (100,000/100)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 individual disk is 100,000 hours, mean time to repair of 10 hours gives mean time to data loss of

$$100{,}000^2/2*10 = 500*10^6 \text{ hours}$$

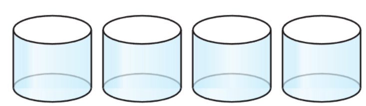
(or 57,000 years) for a mirrored pair of disks

Improvement in Performance via Parallelism

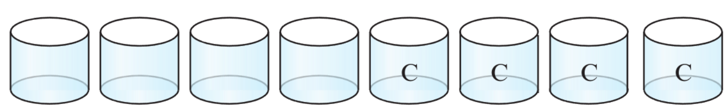
- Two main goals of parallelism in a disk system:
  1. Load balance multiple small accesses to increase throughput
  2. Parallelize large accesses to reduce response time.
- Improve transfer rate by striping data across multiple disks.
- **Bit-level striping** – split the bits of each byte across multiple disks
  - 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
    - Bit level striping is not used much any more
- **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

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.
  - If each disk has M blocks, logical blocks 0 to M – 1 are stored on disk 0, M to 2M – 1 on disk 1(the second disk), and so on, and each disk is mirrored.



(a) RAID 0: nonredundant striping



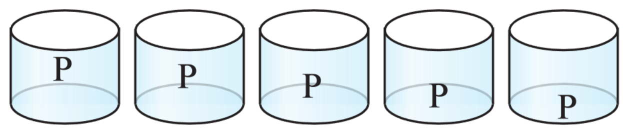
(b) RAID 1: mirrored disks

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
  - 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 nth 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

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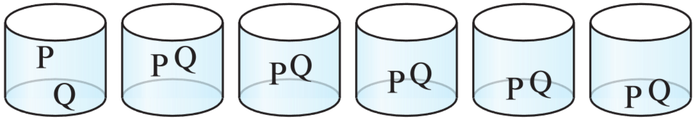
RAID Levels (Cont.)

- **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



(d) RAID 6: P + Q redundancy

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 of extra disk-storage requirements.
  - 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
    - For RAID 1, all blocks of the disks are scanned to see if any pair of blocks on the two disks have different contents.
    - For RAID 5, the disks need to be scanned and parity recomputed for each set of blocks and compared to the stored parity.
    - 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

Thank you