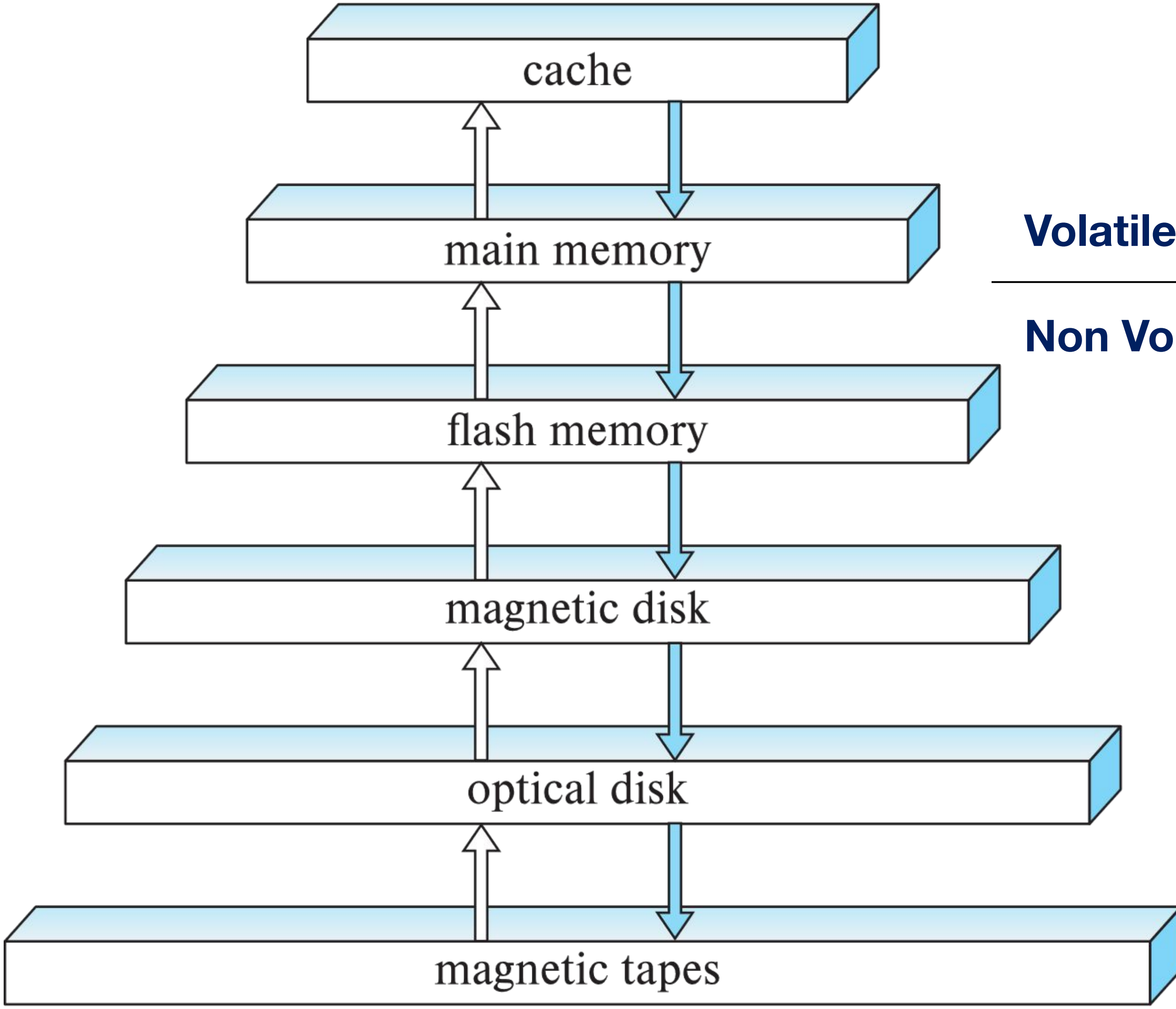
Chapter 12: Physical Storage Systems

Database System Concepts, 7th Ed.

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, as well as batter-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



Primary Storage

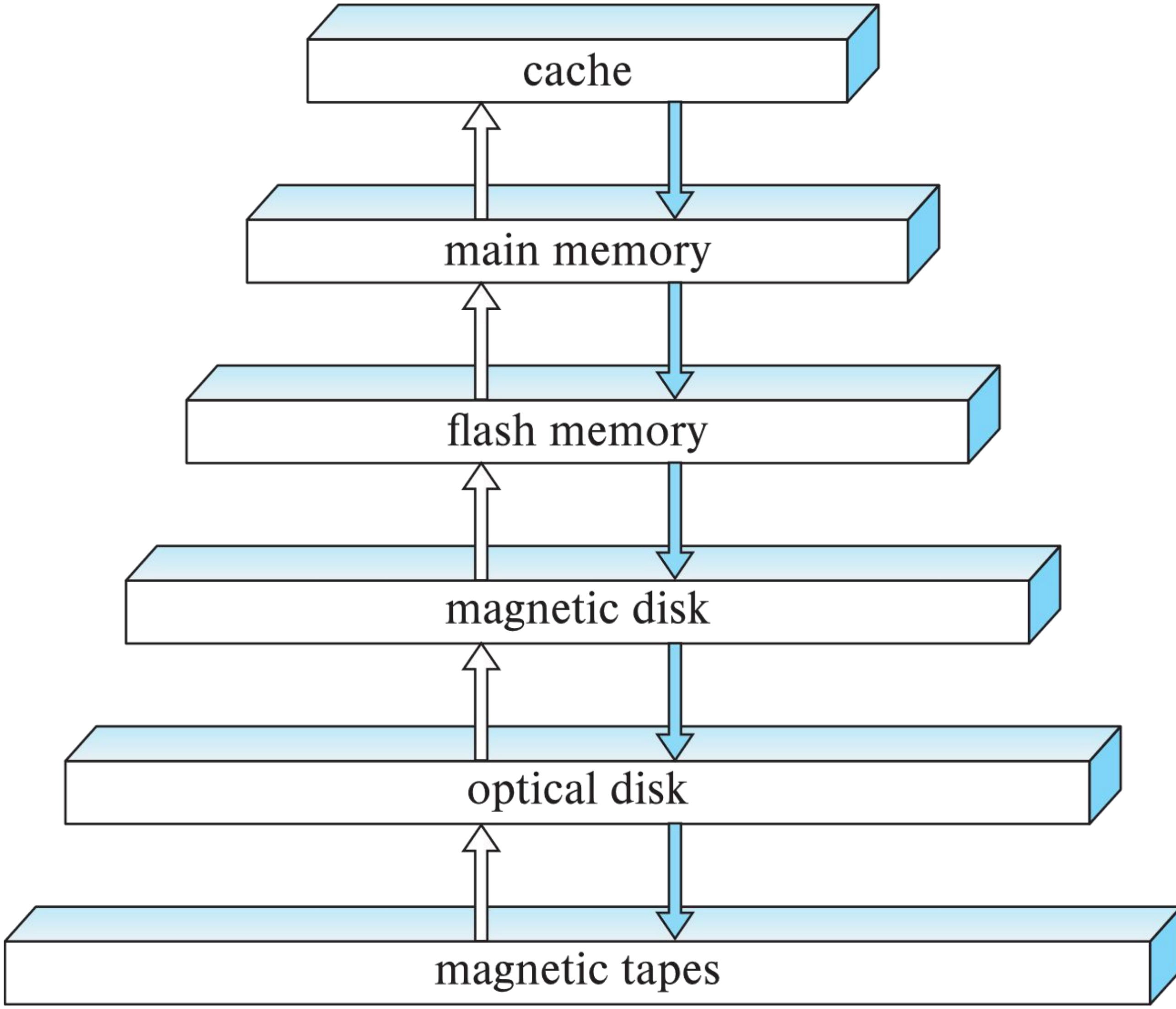
Volatile Storage

Non Volatile Storage

Secondary Storage

Tertiary Storage

Storage Hierarchy: Access Time



1-5 nanoseconds

60-100 nanoseconds
cache-line-at-a-time

20-100 microseconds
page-at-a-time

5-10 milliseconds
page-at-a-time

100+ milliseconds

10-100 seconds or more

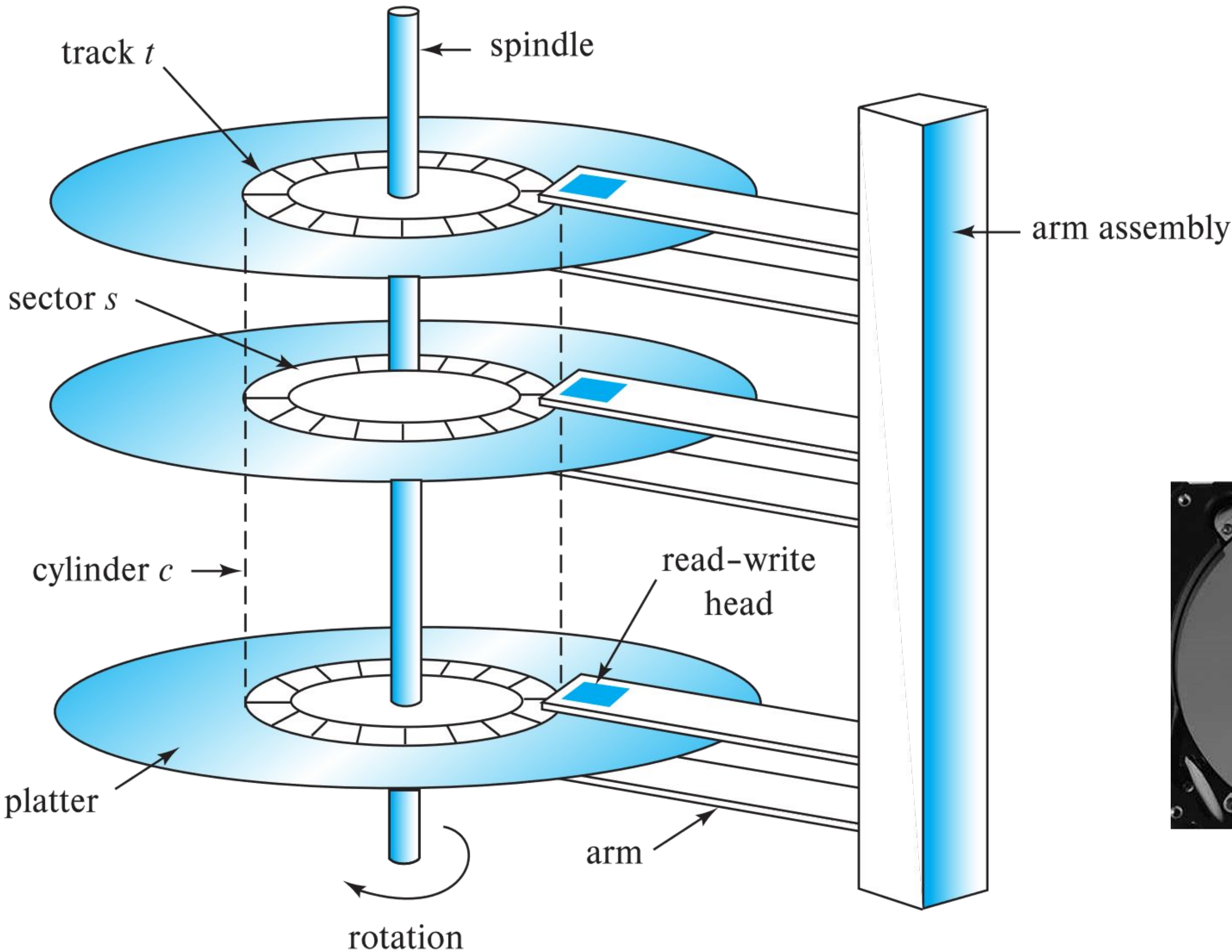
Storage Hierarchy (Cont.)

- **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 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



Schematic diagram of magnetic disk drive

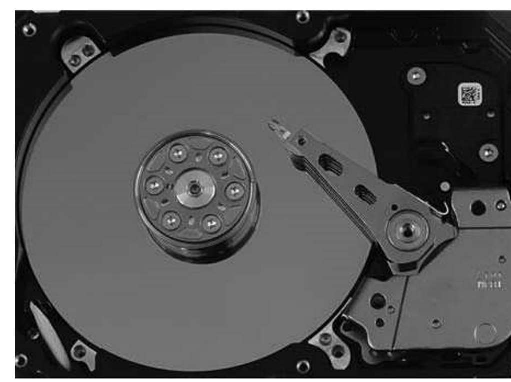


Photo of magnetic disk drive

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.
    - Average seek time is 1/2 the worst case 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
    - 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
- **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

    MTTF= Total time/total unit
  - 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
- **Annualized Failure Rate (AFR):** =((365*24) / MTTF)*100%
  - MTTF=1,200,000 □ AFR = 0.73%
- Suppose MTTF is 1,200,000 hours for a disk. Then, in a system with 1000 disks, how often will a disk fail on average?
  - Answer: on average one will fail every 1200 hours (50 days)
    - Equivalently, 7.3 disks per year

Flash Storage

NOR Flash *is a type of* ***non-volatile*** *memory that retains data even when power is turned off*

- 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
  - ***Page can only be written once***
    - Must be erased to allow rewrite
- **Solid state disks**

  SATA, NVMe, and SAS

  - 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

NVMe SSDs use multiple PCIe lanes, allowing them to transfer large amounts of data in **parallel.**
SATA SSDs are limited to a single channel, creating a bottleneck.

Feature	NOR Flash	NAND Flash
Architecture	Uses a parallel connection of memory cells, allowing random access.	Uses a series connection, optimized for sequential access.
Read Speed	Fast random read access (can access any byte directly).	Fast sequential read but slower random access.
Write & Erase Speed	Slower write and erase speeds.	Faster write and erase speeds.
Endurance (Erase Cycles)	~100,000 to 1,000,000 cycles.	~10,000 to 100,000 cycles.
Storage Density	Lower (few MBs to hundreds of MBs).	Higher (GBs to TBs).
Cost per Bit	Higher (larger cell size).	Lower (smaller cell size).
Power Consumption	Higher due to parallel architecture.	Lower, making it more energy-efficient.
Use Case	Firmware storage (BIOS, bootloaders), embedded systems, automotive, industrial applications.	Mass storage (USB drives, SSDs, SD cards, smartphones).
Execute-in-Place (XIP)	Supports XIP, allowing code execution directly from memory.	Does not support XIP; code must be copied to RAM first.

SSD

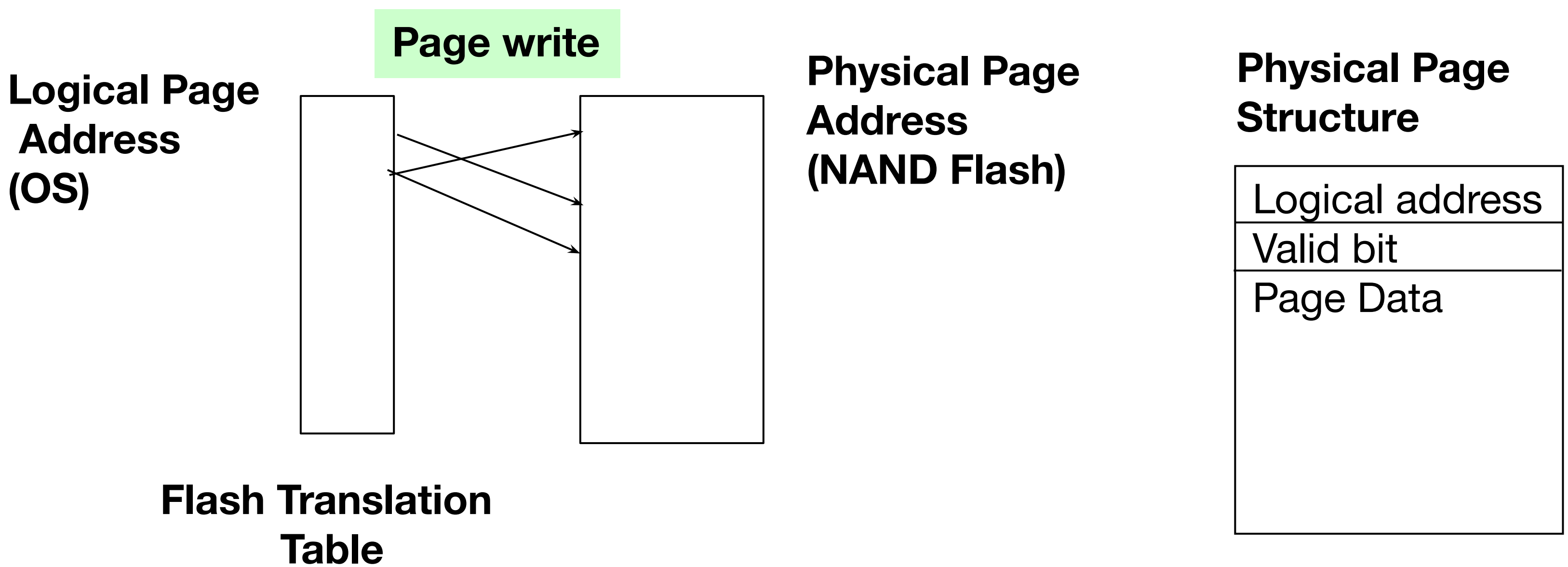
A **Solid-State Drive (SSD)** is a high-speed **non-volatile storage device** that uses **NAND flash memory** to store and retrieve data. Unlike traditional **Hard Disk Drives (HDDs)**, SSDs have no moving parts, making them **faster, more reliable, and more energy-efficient**.

SSDs store data in **NAND flash memory cells**, which are organized into **pages** and **blocks**:

- **Page:** The smallest unit of data storage (typically **4KB to 16KB**).
- **Block:** A group of **pages** (typically **128KB to 4MB**).
- **Erase-Write Mechanism:**
  - **New data is written to an empty page.**
  - **Existing data cannot be overwritten directly**—instead, an entire block must be erased before rewriting.
  - This is why SSDs use **wear leveling** and **garbage collection** to manage data efficiently.

Flash Storage (Cont.)

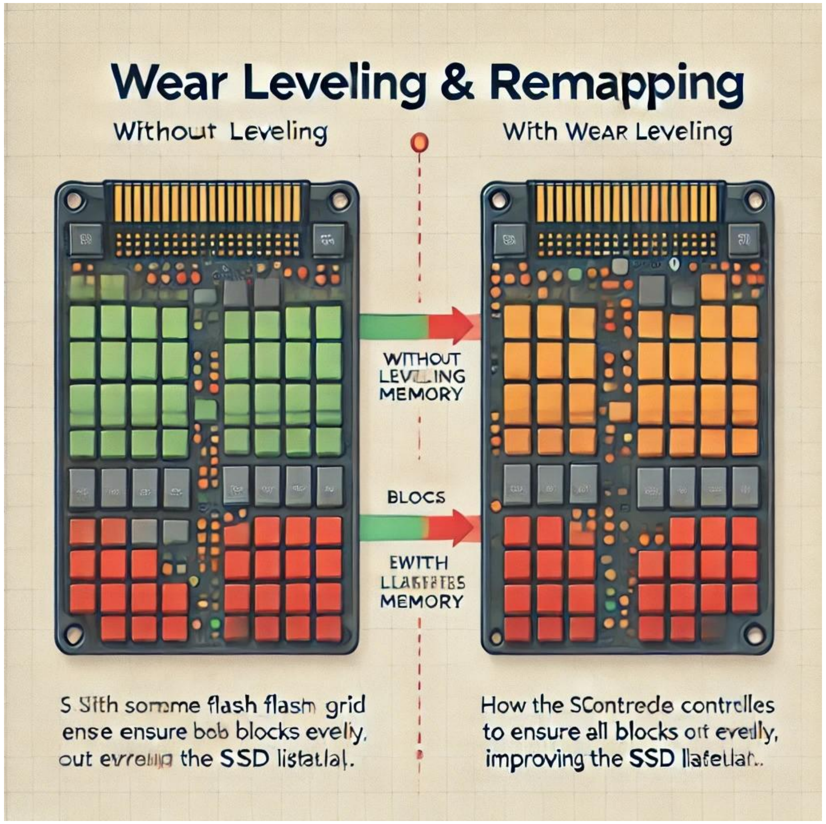
- Erase happens in units of **erase block**
  - Takes 2 to 5 millisecs
  - Erase block typically 256 KB to 1 MB (128 to 256 pages)
- **Remapping** of logical page addresses to physical page addresses avoids waiting for erase [*Erase then rewrite Vs Remap L2P*]
- **Flash translation table** tracks mapping
  - also stored in a label field of flash page
  - remapping carried out by **flash translation layer**



Flash Storage (Cont.)

How Remapping improves:

1. The SSD **writes data to a new, empty page** elsewhere.
2. The logical address now **points to the new physical page**.
3. The old page is marked as **stale** (invalid) and later erased in the background via **Garbage Collection**.

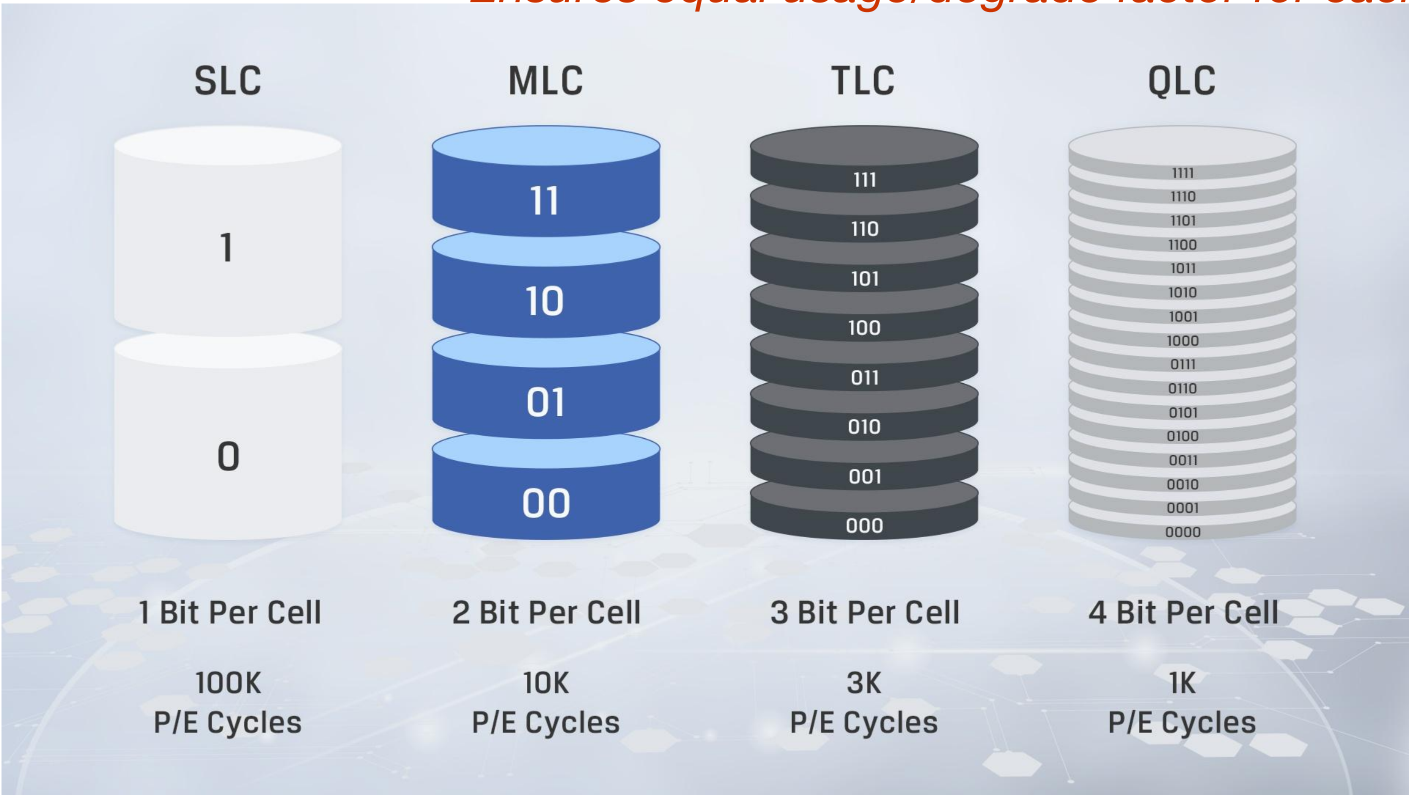


Due to the architecture of NAND flash, rewriting of cells make them weak. Wear leveling and remapping feature also ensures almost equal usage of all the NAND cells.

Flash Storage (Cont.)

- SLC After about 1,00,000 erases (SLC Flash) to as low as 10,000 or 1000 erases (TLC/QLC Flash) erase block becomes unreliable and cannot be used (P/E = Program/Erase)
  - **wear leveling:** store infrequently updated ("cold") data in blocks that have been erased many times already

Ensures equal usage/degrade factor for each cell



Source: Kingston.com

SSD Performance Metrics

- Random reads/writes per second
  - Typical 4 KB 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 (HDD < Hybrid Disks < SSD)

Storage Class Memory

- 3D-XPoint memory technology pioneered by Intel
  3D XPoint *is a revolutionary* ***non-volatile memory (NVM) technology*** *co-developed by* ***Intel and Micron****, designed to bridge the gap between* ***DRAM (fast but volatile) and NAND flash (non-volatile but slower)****. It offers a unique combination of* ***high speed, low latency, and persistence****, making it an ideal solution for storage and memory applications.*
- Available as Intel Optane (Optane SSDs) [Improved performance over traditional Flash Based SSDs]
  - SSD interface shipped from 2017
    - Allows lower latency than flash SSDs
  - Non-volatile memory interface announced in 2018
    - Supports direct access to words, at speeds comparable to main-memory speeds

Optane SSDs stopped productions around 2022 due to high cost and low demand. Current, SSDs use NAND flash based SSDs

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)

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- **Mean time to data (MTTD) loss** depends on mean time to failure (MTTF), and **mean time to repair (MTTR)**
  - 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)

$$MTTD = (MTTF * MTTF) / (2 * MTTR)$$

Improvement in Performance via Parallelism

- Goals of parallelism in a disk system:
  1. Load balance multiple small accesses to increase throughput
  2. Parallelize large accesses to reduce response time.
  3. 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

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  - Not used in practice
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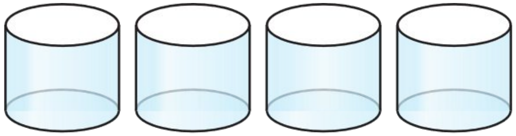
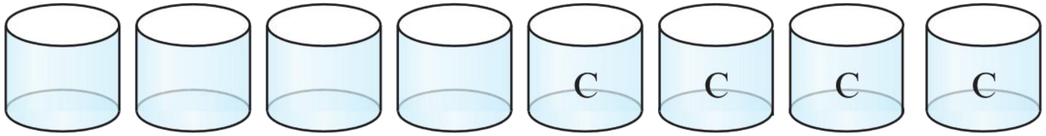
RAID Levels

- **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



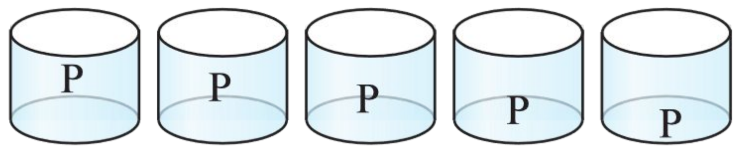
(b) RAID 1: mirrored disks

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
  - 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.



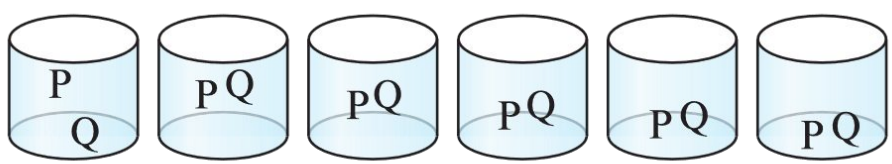
(c) RAID 5: block-interleaved distributed parity

Using this, data can be reconstructed: non fail disks with parity bits

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



(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
  - 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

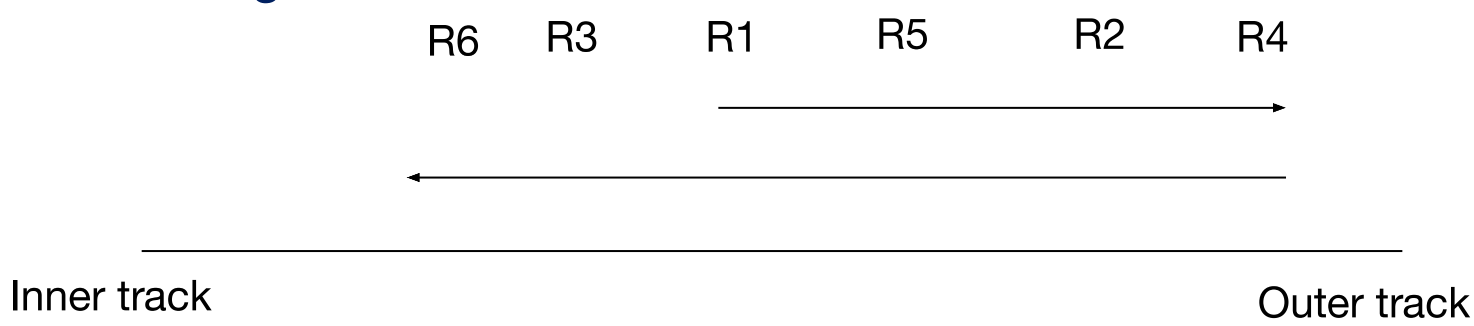
- **Software RAID**: RAID implementations done entirely in software, with no special hardware support
- **Hardware RAID**: RAID implementations with special hardware
  - Use non-volatile RAM to record writes that are being executed
  - Beware: power failure during write can result in corrupted disk
    - 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
      - Full scan of disk may be required!
      - NV-RAM helps to efficiently detect potentially corrupted blocks

Hardware Issues (Cont.)

- **Latent sector 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
- **Spare disks** are kept online, and used as replacements for failed disks immediately on detection of failure
  - Reduces time to recovery greatly
- To avoid single point of failure
  - Redundant power supplies with UPS backup
  - Multiple network controllers/network interconnections

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 reorder block requests so that disk arm movement is minimized
  - **elevator algorithm**



Elevator algorithm:
One directional algorithm, while reading going from outer to inner completely, the moving backwards. Requests can be reordered to bring efficiency.

Optimization of Disk Block Access (Cont.)

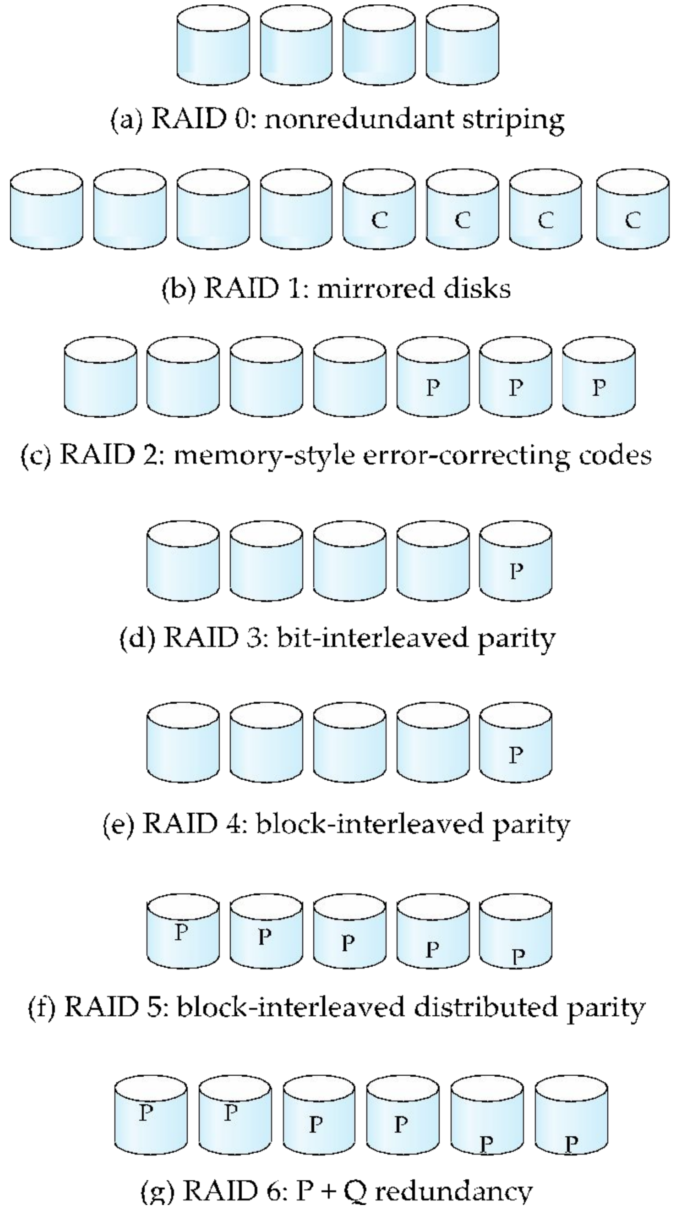
- **File organization**
  - Allocate blocks of a file in as contiguous a manner as possible
  - Allocation in units of **extents**
  - Files may get **fragmented**
    - E.g. if free blocks on disk are scattered, and newly created file has its blocks scattered over the disk
    - Sequential access to 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**

End of Chapter 12

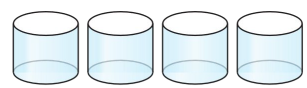
Magnetic Tapes

- Hold large volumes of data and provide high transfer rates
  - Few GB for DAT (Digital Audio Tape) format, 10-40 GB with DLT (Digital Linear Tape) format, 100 GB+ with Ultrium format, and 330 GB with Ampex helical scan format
  - Transfer rates from few to 10s of MB/s
- Tapes are cheap, but cost of drives is very high
- Very slow access time in comparison to magnetic and optical disks
  - limited to sequential access.
  - Some formats (Accelis) provide faster seek (10s of seconds) at cost of lower capacity
- Used mainly for backup, for storage of infrequently used information, and as an off-line medium for transferring information from one system to another.
- Tape jukeboxes used for very large capacity storage
  - Multiple petabyes (10^{15} bytes)

Figure 10.03


(a) RAID 0: nonredundant striping
C C C C
(b) RAID 1: mirrored disks
P P P
(c) RAID 2: memory-style error-correcting codes
P
(d) RAID 3: bit-interleaved parity
P
(e) RAID 4: block-interleaved parity
P P P P P
(f) RAID 5: block-interleaved distributed parity
P P P P P P
(g) RAID 6: P + Q redundancy

Disk 1	Disk 2	Disk 3	Disk 4
B_1	B_2	B_3	B_4
P_1	B_5	B_6	B_7
B_8	P_2	B_9	B_{10}
⋮	⋮	⋮	⋮



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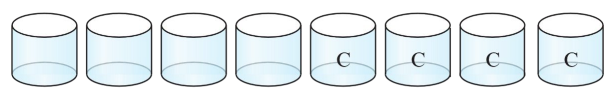
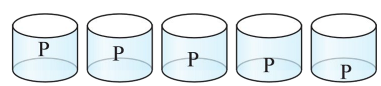
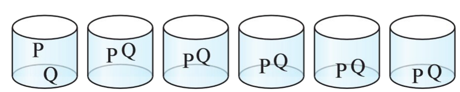


(b) RAID 1: mirrored disks



(c) RAID 5: block-interleaved distributed parity



(d) RAID 6: P + Q redundancy