

Hard Disk Drives (HDD)
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Solid State Drives (SSD)
oooooooooooo

RAID
oooooooooooooooo

4th Slide Set Operating Systems

Prof. Dr. Christian Baun

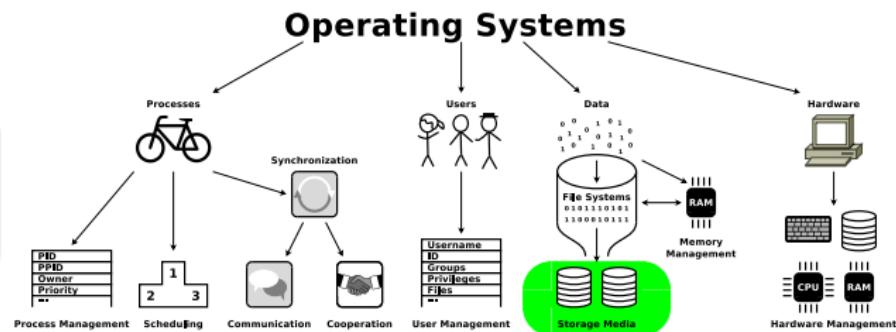
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Learning Objectives of this Slide Set

- At the end of this slide set You know/understand...
 - the structure, functioning and characteristics of **Hard Disk Drives**
 - the structure, functioning and characteristics of **Solid State Drives**
 - the functioning and the most commonly implemented variants of Redundant Array of Independent Disks (**RAID**)

By knowing how HDDs and SSDs work, you will also understand better how file systems (⇒ slide set 6) work and their design principles

Exercise sheet 4 repeats the contents of this slide set which are relevant for these learning objectives



Hard Disk Drives

- HDDs are approx. 100 times less expensive per bit versus main memory and they offer approx. 100 times more capacity
 - Drawback: Accessing data on HDDs is approx. 1000 times slower
- Reason for the poorer **access time**:
 - HDDs are mechanical devices
 - They contain one or more discs, rotating with 4200, 5400, 7200, 10800, or 15000 revolutions per minute (RPM)
- For each side of each disc (**platter**), an arm exists with a **read-and-write head**
 - The read-and-write head is used to detect and modify the magnetization of the material
 - The distance between disk and head is approx. 20 nanometers
- Also, HDDs have a cache (usually \leq 32 MB)
 - This cache buffers read and write operations

Logical Structure of Hard Disk Drives (1/2)

- The surfaces of the **platters** (discs) are magnetized in circular **tracks** by the heads
- All tracks on all disks at a specific arm position are part of a **cylinder**
- The tracks are divided into logical units (segments of a circle), which are called **blocks** or **sectors**
 - Typically, a sector contains 512 bytes payload
 - Sectors are the smallest addressable units of HDDs

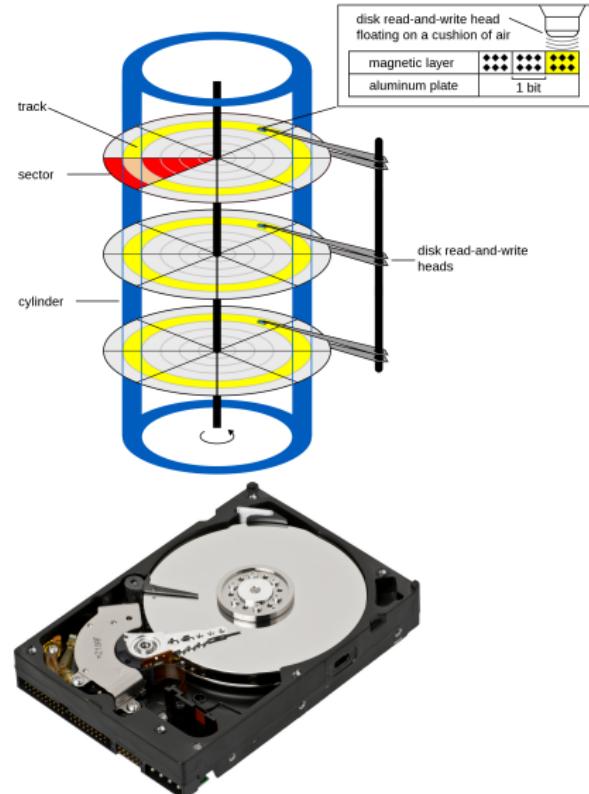


Image source (structure): Henry Mühlfordt. Wikimedia
(CC-BY-SA-1.0)

Image source (HDD): purepng.com (CC0)

Logical Structure of Hard Disk Drives (2/2)

- If data need be modified, the entire sector must be read and rewritten
- Today, **clusters** are addressed by the software (see slide set 6)
 - Clusters are groups of sectors with a fixed size, e.g. 4 or 8 kB
 - In file systems of modern operating systems, clusters are the smallest addressable unit of HDDs

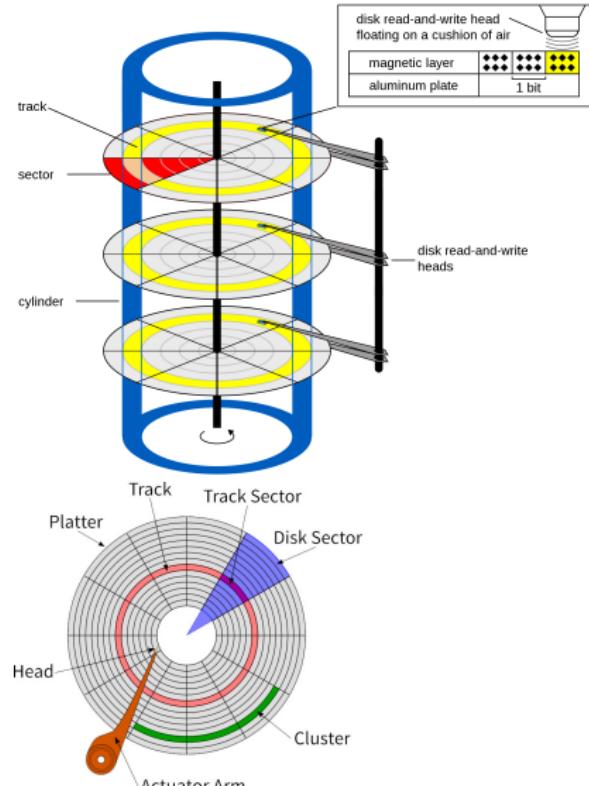


Image source (structure): Henry Mühlpfordt. Wikimedia
(CC-BY-SA-1.0)

Image source (platter): Tim Bielawa. The Linux Sysadmins Guide to Virtual Disks (CC-BY-SA-4.0)

Addressing Data on Hard Disk Drives

- HDDs with a capacity \leq 8 GB use the **Cylinder-Head-Sector addressing**
 - CHS faces several limitations:
 - The Parallel ATA interface and the BIOS offer just...
 - 16 bits for the cylinders (up to 65,536)
 - 8 bits for the heads (up to 255. Head number 0 is not used)
 - 8 bits for the sectors/track (up to 255. Sector number 0 is not used)
 - ≤ 7.844 GB can be addressed this way
 - 1024 cylinders * 255 heads * 63 sectors/track * 512 bytes/sector = 8,422,686,720 bytes
 - $8,422,686,720$ bytes / 1024 / 1024 / 1024 = 7.844 GB
 - No 2.5" or 3.5" HDD contains > 16 heads!!!
 - Logical heads were used
 - HDDs with a capacity > 7.844 GB use **Logical Block Addressing (LBA)**
 - All sectors are numbered consecutively beginning with 0

Logical Block Addressing (LBA)

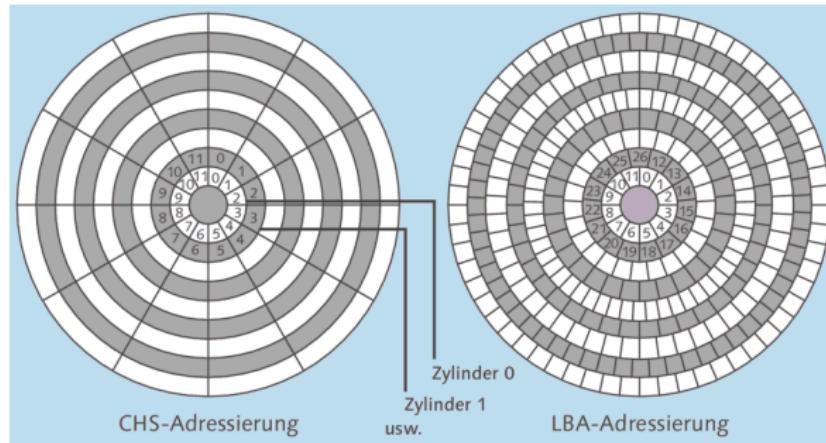


Image source

IT-Handbuch für
Fachinformatiker.
Sascha Kersken.
6th edition.
Rheinwerk Verlag

- When CHS addressing is used, all tracks contain **the same number of sectors**
 - Each sector stores 512 bytes of payload
- Drawback: **Storage capacity is wasted**, because the data density decreases from the inner tracks to the outer tracks
- When LBA is implemented, this drawback does not exist

Required Time to access Data on HDDs

- The access time is an important performance factor
- 2 factors influence the access time of HDDs

① Average Seek Time

- The time that it takes for the arm to reach a desired track
- Is for modern HDDs between 5 and 15 ms

② Average Rotational Latency Time

- Delay of the rotational speed, until the required disk sector is located under the head
- Depends entirely on the rotational speed of the disks
- Is for modern HDDs between 2 and 7.1 ms

$$\text{Average Rot. Lat. Time [ms]} = \frac{1000 \frac{[\text{ms}]}{\text{sec}} \times 60 \frac{[\text{sec}]}{\text{min}} \times 0.5}{\frac{\text{revolutions}}{\text{min}}} = \frac{30,000 \frac{[\text{ms}]}{\text{min}}}{\frac{\text{revolutions}}{\text{min}}}$$

Why does the equation contain 0.5 ?

Once the head has reached the right track, on average a half rotation of the disk must be waited for the correct sector to be under the head \implies Average Rotational Latency Time = half Rotational Latency Time

Solid State Drives (SSD)

- Are sometimes falsely called Solid State Disks

- Do not contain moving parts

- Benefits:

- Fast access time
- Low power consumption
- No noise generation
- Mechanical robustness
- Low weight
- The location of data does not matter \Rightarrow defragmenting makes no sense

- Drawbacks:

- Higher price compared with HDDs of the same capacity
- Secure delete or overwrite is hard to implement
- Limited number of program/erase cycles



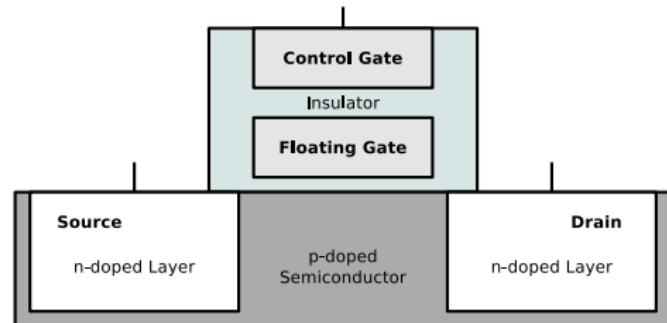
Image (SSD): Thomas Springer. Wikimedia (CC0)



Image (HDD): Erwan Velu. Wikimedia (CC-BY-SA-1.0)

Functioning of Flash Memory

- Data is stored as electrical charges
- In contrast to main memory, no electricity is required to keep the data



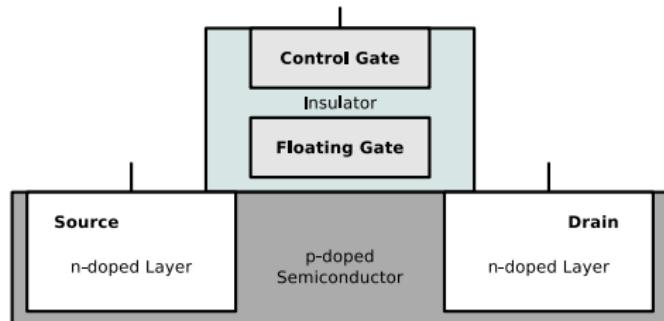
- Each flash memory cell is a transistor and has 3 connectors
 - **Gate** = control electrode
 - **Drain** = electrode
 - **Source** = electrode
- The floating gate stores electrons (data)
 - Completely surrounded by an insulator
 - Electrical charge remains stable for years

Well written explanation about the functioning of flash memory

Benjamin Benz. *Die Technik der Flash-Speicherkarten.* c't 23/2006

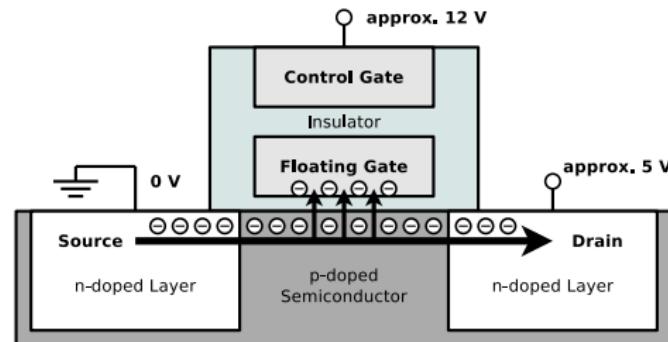
Reading Data from Flash Memory Cells

- A positively doped (p) semiconductor separates the 2 negatively doped (n) electrodes drain and source
 - Equal to a npn transistor, the npn passage is not conductive without a base current
- Above a certain positive voltage (5V) at the gate (**threshold**) a n-type channel is created in the p-area
 - Current can flow between source and drain through this channel
- If the floating gate contains electrons, the threshold is different
 - A higher positive voltage at the gate is required, so that current can flow between source and drain
 - **This way the stored value of the flash memory cell is read out**



Writing Data into Flash Memory Cells

- Data is stored inside flash memory cells by using **Fowler-Nordheim tunneling**



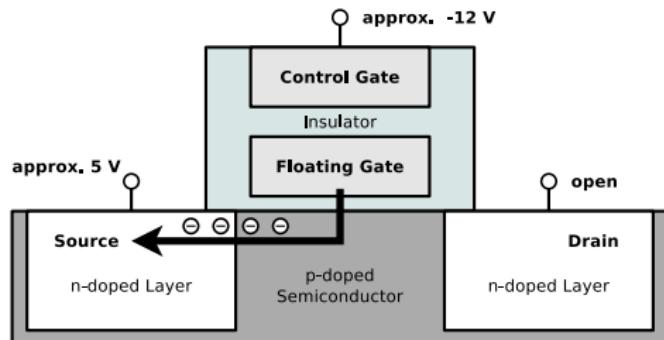
- A positive voltage (5V) is applied to the control gate
 - As a result, electrons can flow between source and drain
- If the high positive voltage is sufficient high (6 to 20V), some electrons are tunneled (\Rightarrow Fowler-Nordheim tunneling) through the insulator into the floating gate
- This method is also called **Channel Hot Electron Injection**

Recommended Source

Flash memory. Alex Paikin. 2004. http://www.hitequest.com/Kiss/Flash_terms.htm

Erasing Data in Flash Memory Cells

- For erasing a flash memory cell, a negative voltage (-6 to -20V) is applied at the control gate
 - As a result, electrons are tunneled in the reverse direction from the floating gate
- The insulating layer, which surrounds the floating gate, suffers from each erase cycle
 - At some point the insulating layer is no longer sufficient to hold the charge in the floating gate
 - For this reason, flash memory survives only a limited number of program/erase cycles



Functioning of Flash Memory

- Memory cells are connected to **blocks** and (depending on the structure also in) **pages**
 - A block always contains a fixed number of pages
 - Write/erase operations can only be carried out for entire pages or blocks
⇒ Write and erase operations are more complex than read operations
 - If data in a page need to be modified, the entire block must be erased
 - ① To do this, the block is copied into a buffer memory (cache)
 - ② Inside the cache, the data is modified
 - ③ Next, the block is erased from the flash memory
 - ④ Finally, the modified block is written into the flash memory
- 2 types of flash memory exist:
 - **NOR memory** (just blocks)
 - **NAND memory** (blocks and pages)

The circuit symbol indicates the way, the memory cells are connected

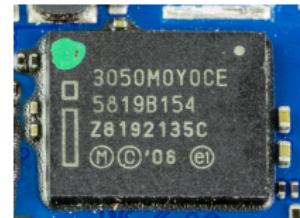
This influences the capacity and access time (latency)

NOR Memory

- Each memory cell has its data line
 - Benefit:
 - Random access for read and write operations
⇒ Better latency compared with NAND memory
 - Drawback:
 - More complex (⇒ expensive) construction
 - Higher power consumption than NAND memory
 - Typically small capacities (\leq 32 MB)
- Does not contain pages
 - The memory cells are grouped together to blocks
 - Typical block sizes: 64, 128 or 256 kB
- No random access for erase operations
 - Erase operations can only be done for entire blocks

Fields of application

Industrial environment (e.g. automotive), storing the firmware of a computer system



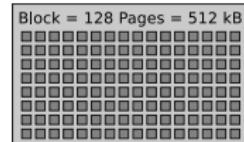
NOR flash memory (top image) on the iPhone 3G mainboard (bottom image)



Images: Raimond Spekking.
Wikimedia (CC-BY-SA-4.0)

NAND Memory

- The memory cells are grouped to pages
 - Typical page size: 512-8192 bytes
 - Each page has its data line
 - Each block consists of a number of pages
 - Typical block sizes: 32, 64, 128 or 256 pages
- Benefit:
 - Lesser data lines \Rightarrow requires < 50% of the surface area of NOR memory
 - Lower manufacturing costs compared with NOR flash memory
- Drawback:
 - No random access \Rightarrow Poorer latency compared with NOR memory
 - Read and write operations can only be carried out for entire pages
 - Erase operations can only be carried out for entire blocks

Page
4 kB

Fields of application

USB flash memory drives,
SSDs, memory cards



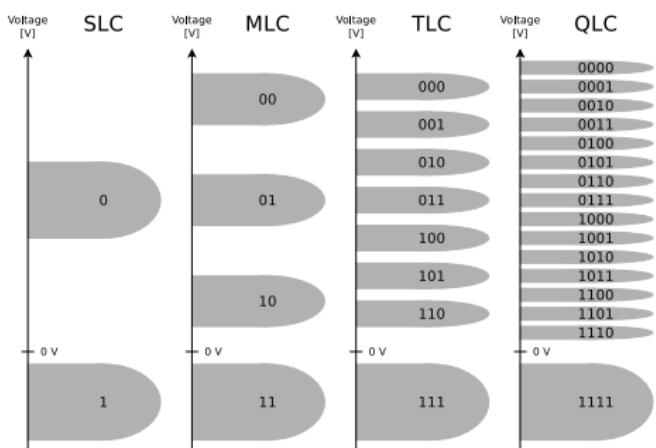
Single/Multi/Triple/Quad-Level Cell

- 4 types of NAND flash memory exist

- QLC memory cells store 4 bits
- TLC memory cells store 3 bits
- MLC memory cells store 2 bits
- SLC memory cells store 1 bit

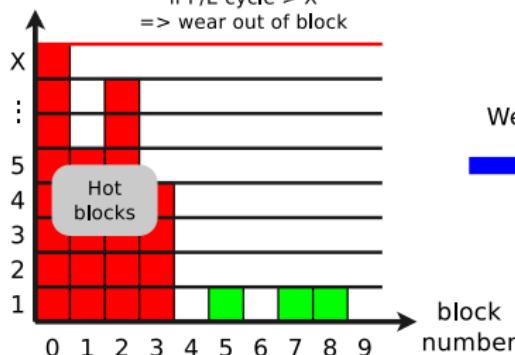
- SLC storage...

- is most expensive
- provides the best write speed
- survives most program/erase cycles

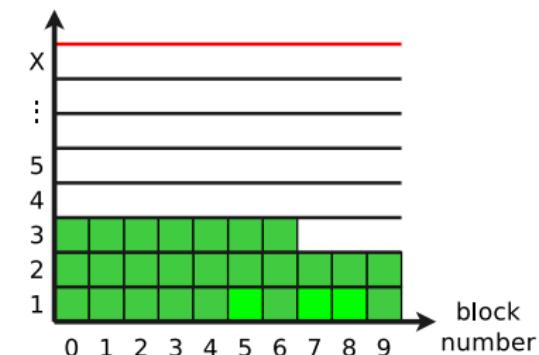


- SLC memory survives approx. 100,000 - 300,000 program/erase cycles
- MLC memory survives approx. 10,000 program/erase cycles
- TLC and QLC memory survives approx. 1,000 program/erase cycles
- Also memory cells exist, which survive millions of program/erase cycles

Wear Leveling

Program/Erase
count (P/E)if P/E cycle > X
=> wear out of blockProgram/Erase
count (P/E)

Wear Leveling



- Wear leveling algorithms evenly distribute write operations
- File systems, which are designed for flash memory, and therefore minimize write operations, are e.g. JFFS, JFFS2, YAFFS and LogFS
 - JFFS contains its own wear leveling algorithm
 - This is often required in embedded systems, where flash memory is directly connected

Latency of Hard Disk Drives

- The performance of CPUs, cache and main memory is growing faster than the data access time (*latency*) of HDDs:

- HDDs**

1973: IBM 3340, 30 MB capacity, 30 ms data access time
1989: Maxtor LXTI00S, 96 MB capacity, 29 ms data access time
1998: IBM DHEA-36481, 6 GB capacity, 16 ms data access time
2006: Maxtor STM320820A, 320 GB capacity, 14 ms data access time
2011: Western Digital WD30EZRSCTL, 3 TB capacity, 8 ms data access time
2018: Seagate BarraCuda Pro ST14000DM001, 14 TB capacity, 4-5 ms data access time

- CPUs**

1971: Intel 4004, 740 kHz clock speed
1989: Intel 486DX, 25 Mhz clock speed
1997: AMD K6-2, 550 Mhz clock speed
2007: AMD Opteron Santa Rosa F3, 2.8 GHz clock speed
2010: Intel Core i7 980X Extreme (6 Cores), 3.33 Ghz clock speed
2018: AMD Ryzen Threadripper 2990WX (32 Cores), 3 Ghz clock speed
2020: AMD Ryzen Threadripper 3990X (64 Cores), 2.9 Ghz clock speed

- The latency of **SSDs** is $\leq 1 \mu\text{s}$ $\Rightarrow \approx$ factor 100 better than HDDs
 - But the gap grows because of interface limitations and multiple CPU cores
- Further challenge
 - Storage drives can fail \Rightarrow risk of data loss
- Enhance **latency** and **reliability** of HDDs and SSDs \Rightarrow **RAID**

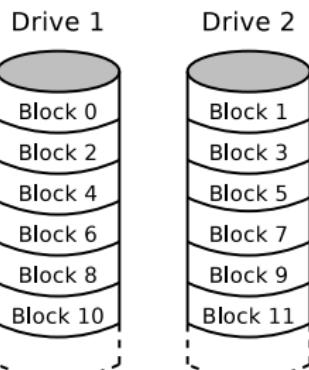
Redundant Array of independent Disks (RAID)

- The performance of the HDDs can not be improved infinitely
 - HDDs contain moving parts
 - Physical boundaries must be accepted
- One way to avoid the given limitations in terms of speed, capacity and reliability, is the parallel use multiple components
- A RAID consists of multiple drives (HDDs or SSDs)
 - For users and their processes, a RAID behaves like a single large drive
- Data is distributed across the drives of a RAID system
 - The RAID level specifies how the data is distributed
 - The most commonly used RAID levels are RAID 0, RAID 1 and RAID 5

Patterson, David A., Garth Gibson, and Randy H. Katz, **A Case for Redundant Arrays of Inexpensive Disks (RAID)**, Vol. 17. No. 3, ACM (1988)

RAID 0 – Striping – Acceleration without Redundancy

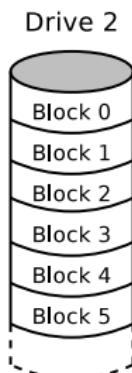
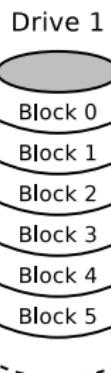
- No redundancy
 - Increases only the data rate
- Drives are partitioned into blocks of equal size
- If read/write operations are big enough (> 4 or 8 kB), the operations can be carried out in parallel on multiple drives or on all drives



- In the event of a drive failure, not the entire data can be reconstructed
 - Only small files, which are stored entirely on the remaining drives, can be reconstructed (in theory)
- RAID 0 should only be used when security is irrelevant or backups are created at regular intervals

RAID 1 – Mirroring

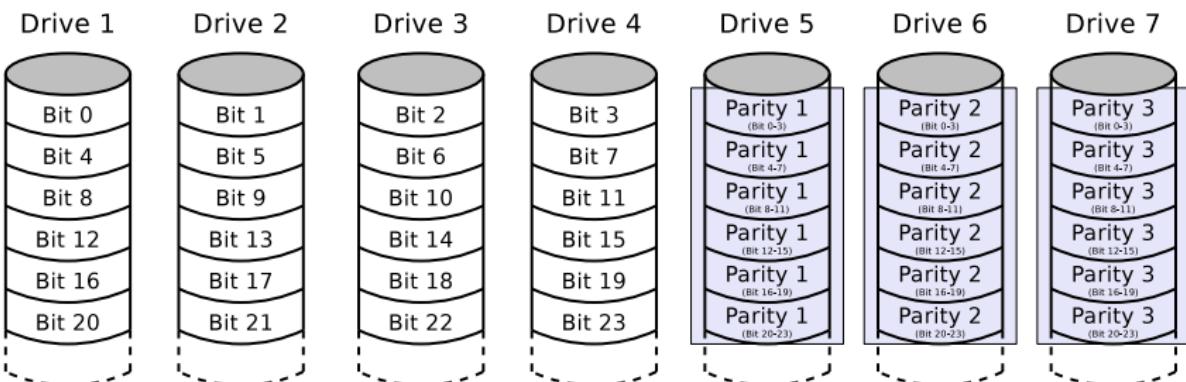
- At least 2 drives of the same capacity store identical data
 - If the drives are of different sizes, RAID 1 provides only the capacity of the smallest drive
- Failure of a single drive does not cause any data loss
 - Reason: The remaining drives store the identical data
- A total loss occurs only in case of the failure of all drives



- Any change of data is written on all drives
- Not a backup replacement
 - Corrupted file operations or virus attacks take place on all drives
- The read performance can be increased by intelligent distribution of requests to the attached drives

RAID 2 – Bit-Level Striping with Hamming Code Error Correction

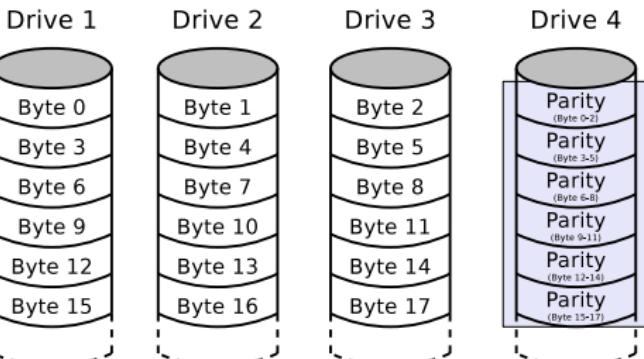
- Each sequential bit is stored on a different drive
 - Bits, which are powers of 2 (1, 2, 4, 8, 16, etc.) are parity bits



- The individual parity bits are distributed over multiple drives
⇒ increases the throughput
- Was used only in mainframes
 - Is no longer relevant

RAID 3 – Byte-level Striping with Parity Information

- Parity information is stored on a dedicated parity drive

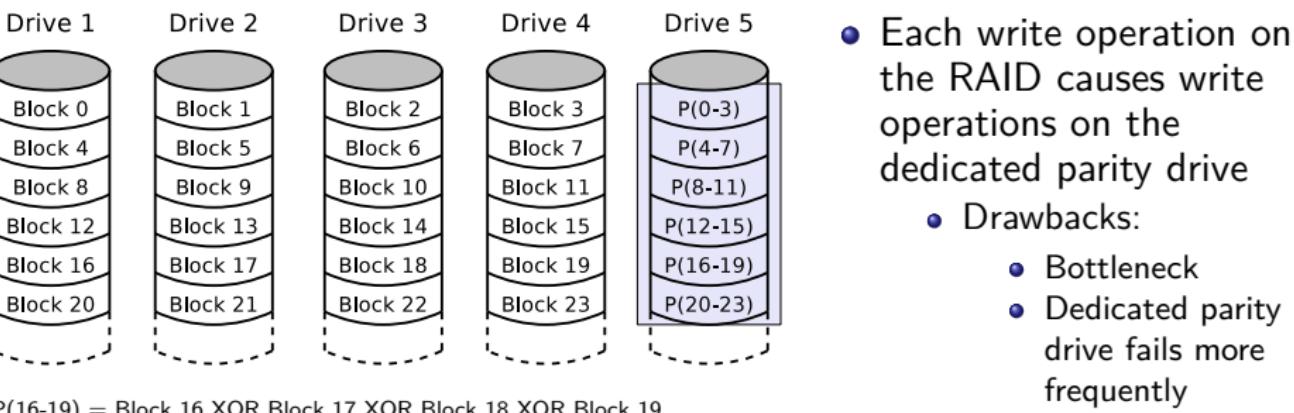


- Each write operation on the RAID causes write operations on the dedicated parity drive
⇒ bottleneck
- Was replaced by RAID 5

Payload drives	Sum	even/odd	Parity drive
Bits are 0 + 0 + 0	⇒ 0	⇒ Sum is even	⇒ Sum bit 0
Bits are 1 + 0 + 0	⇒ 1	⇒ Sum is odd	⇒ Sum bit 1
Bits are 1 + 1 + 0	⇒ 2	⇒ Sum is even	⇒ Sum bit 0
Bits are 1 + 1 + 1	⇒ 3	⇒ Sum is odd	⇒ Sum bit 1
Bits are 1 + 0 + 1	⇒ 2	⇒ Sum is even	⇒ Sum bit 0
Bits are 0 + 1 + 1	⇒ 2	⇒ Sum is even	⇒ Sum bit 0
Bits are 0 + 1 + 0	⇒ 1	⇒ Sum is odd	⇒ Sum bit 1
Bits are 0 + 0 + 1	⇒ 1	⇒ Sum is odd	⇒ Sum bit 1

RAID 4 – Block-level Striping with Parity Information

- Parity information is stored at a dedicated parity drive
- Difference to RAID 3:
 - Not individual bits or bytes, but blocks (**chunks**) are stored

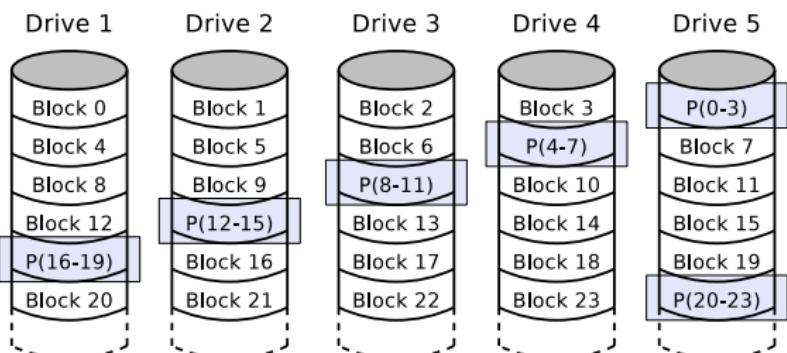


- Each write operation on the RAID causes write operations on the dedicated parity drive
- Drawbacks:
 - Bottleneck
 - Dedicated parity drive fails more frequently

- Seldom implemented, because RAID 5 does not face these drawbacks
- The company NetApp implements RAID 4 in their NAS servers
 - e.g. NetApp FAS2020, FAS2050, FAS3040, FAS3140, FAS6080

RAID 5 – Block-level Striping with distributed Parity Information

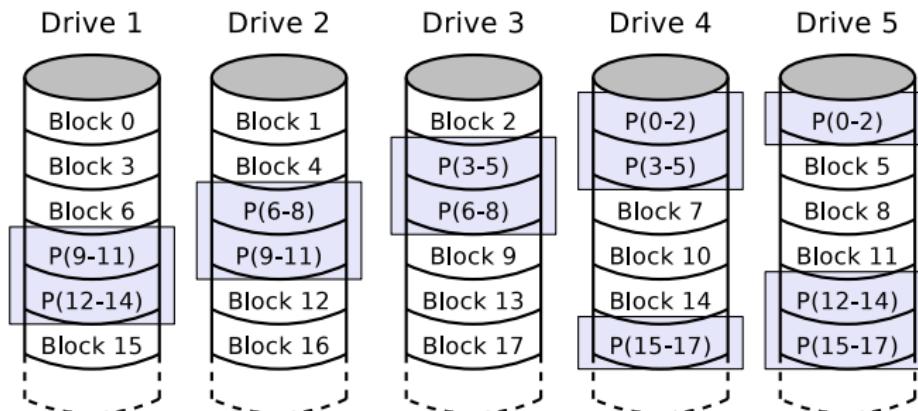
- Payload and parity information are distributed to all drives
- Benefits:
 - High throughput
 - High security level against data loss
 - No bottleneck



$$P(16-19) = \text{block 16 XOR block 17 XOR block 18 XOR block 19}$$

RAID 6 – Block-level Striping with double distributed Parity Information

- Functioning is similar to RAID 5
 - But it can handle the simultaneous failure of up to 2 drives
- In contrast to RAID 5...
 - is the availability better, but the write performance is lower
 - is the effort to write the parity information higher



Summary of the RAID Levels

If you want...

the best performance and don't care about availability \Rightarrow RAID 0

the best availability and don't care about performance \Rightarrow RAID 1

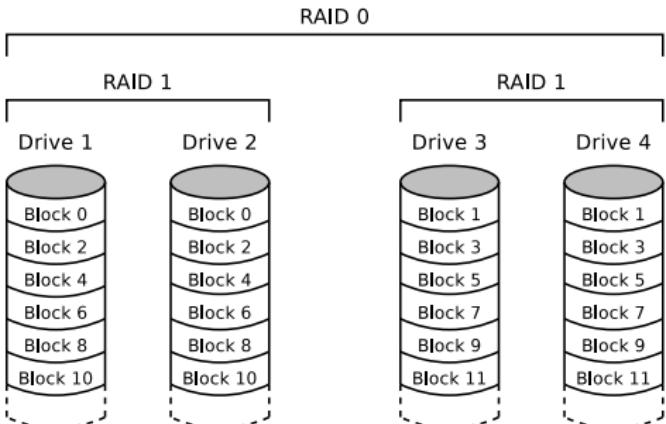
a combination of performance and availability \Rightarrow RAID 5 or RAID 6

RAID	n (number of drives)	k (net capacity)	Allowed to fail	Performance (read)	Performance (write)
0	≥ 2	n	0 (none)	$n * X$	$n * X$
1	≥ 2	1	$n - 1$ drives	$n * X$	X
2	≥ 3	$n - [\log_2 n]$	1 drive	variable	variable
3	≥ 3	$n - 1$	1 drive	$(n - 1) * X$	$(n - 1) * X$
4	≥ 3	$n - 1$	1 drive	$(n - 1) * X$	$(n - 1) * X$
5	≥ 3	$n - 1$	1 drive	$(n - 1) * X$	$(n - 1) * X$
6	≥ 4	$n - 2$	2 drives	$(n - 2) * X$	$(n - 2) * X$

- X is the performance of a single drive during read or write
- The maximum possible performance in theory is often limited by the controller and the computing power of the CPU

If the drives of a RAID 1 have different capacities, the net capacity of a RAID 1 is equal to the capacity of its smallest drive

RAID Combinations



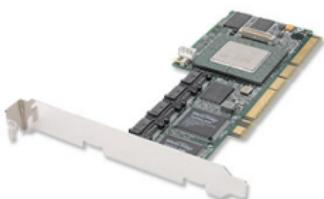
- Usually RAID 0, 1 or 5 is used
- In addition to the popular RAID levels, several RAID combinations exist
 - At least 2 RAIDs are combined to a bigger RAID

Examples

- RAID 00: Multiple RAID 0 are connected to a RAID 0
- RAID 01: Multiple RAID 0 are connected to a RAID 1
- RAID 05: Multiple RAID 0 are connected to a RAID 5
- RAID 10: Multiple RAID 1 are connected to a RAID 0 (**see figure**)
- RAID 15: Multiple RAID 1 are connected to a RAID 5
- RAID 50: Multiple RAID 5 are connected to a RAID 0
- RAID 51: Multiple RAID 5 are connected to a RAID 1

Hardware / Host / Software RAID (1/2)

Image Source: Adaptec



Adaptec SATA RAID 2410SA

• Hardware RAID

- A RAID controller with a processor does the calculation of the parity information and monitors the state of the RAID

Benefit: Operating system independent
No additional CPU load

Drawback: High price (approx. € 200)



Adaptec SATA II RAID 1220SA

• Host RAID

- Either an inexpensive RAID controller or the chipset provide the RAID functionality
- Usually only supports RAID 0 and RAID 1

Benefit: Operating system independent
Low price (approx. € 50)

Drawback: Additional CPU load
Possible dependence of rare hardware

Hardware / Host / Software RAID (2/2)

- **Software RAID**

- Linux, Windows and MacOS allow to connect drives to a RAID without a RAID controller

Benefit: No cost for additional hardware

Drawback: Operating system dependent
Additional CPU load

- Example: Create a RAID 1 (`md0`) with the partitions `sda1` and `sdb1`:

```
mdadm --create /dev/md0 --auto md --level=1  
--raid-devices=2 /dev/sda1 /dev/sdb1
```

- Obtain information about any software RAID in the system:

```
cat /proc/mdstat
```

- Obtain information about a specific software RAID (`md0`):

```
mdadm --detail /dev/md0
```

- Remove partition `sdb1` and add partition `sdc1` to the RAID:

```
mdadm /dev/md0 --remove /dev/sdb1  
mdadm /dev/md0 --add /dev/sdc1
```