4th Slide Set
Operating Systems

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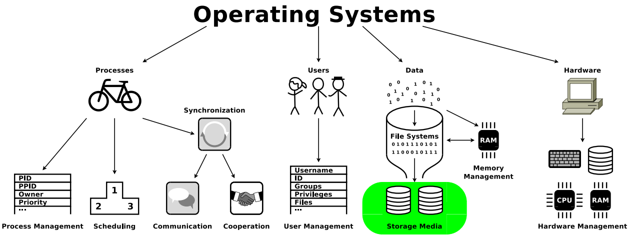
Learning Objectives of this Slide Set

- 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** (disks) 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

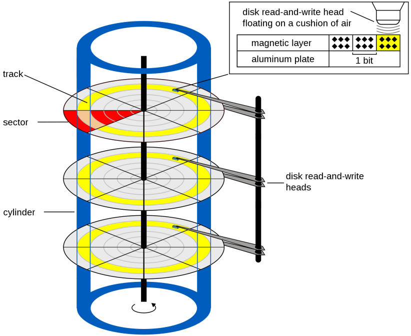
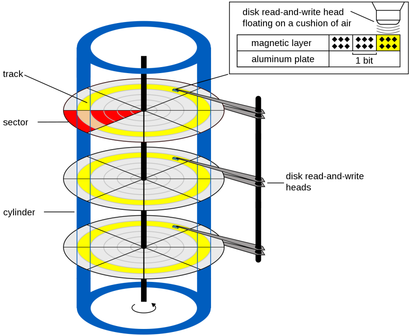


Image source (structure): Henry Mühlpfordt. Wikimedia (CC-BY-SA-1.0)
Image source (HDD): purepng.com (CC0)

Logical Structure of Hard Disk Drives (2/2)

- If data needs to 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



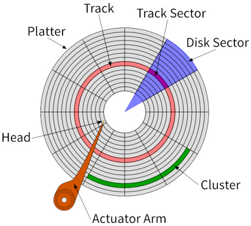


Image source (structure): Henry Mühlpfordt. Wikimedia (CC-BY-SA-1.0)
Image source (platter): Tim Bielawa. The Linux Sysadmins Guide to Virtual Disks (CC-BY-SA-4.0)

Addressing Data on Hard Disk Drives

- HDDs with a capacity $\leq$ 8 GB use the ***C**ylinder-**H**ead-**S**ector 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)
- $\leq$ 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)

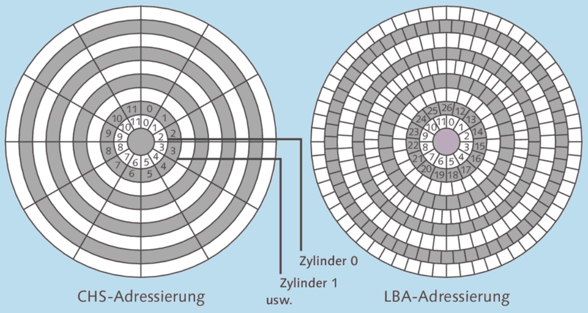


Image source

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 $\Longrightarrow$ 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 $\Longrightarrow$ defragmenting makes no sense

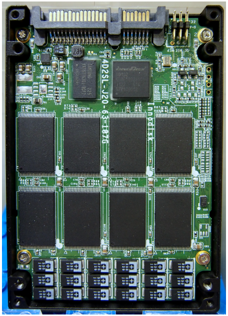


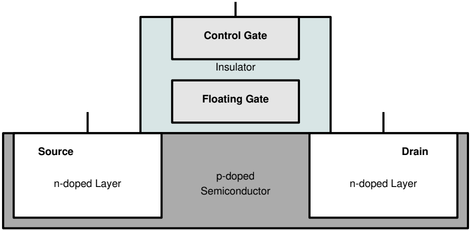
Image (SSD): Thomas Springer. Wikimedia (CC0)

Image (HDD): Own work

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

Functioning of Flash Memory

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



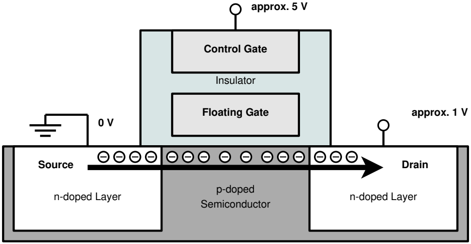
- Each flash memory cell is a transistor and has 3 connectors
  - **Gate** = control electrode
  - **Drain** = electrode
  - **Source** = electrode
- The floating gate stores electrons (data)
  - Completely surrounded by an insulator
  - Electrical charge remains stable for years

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

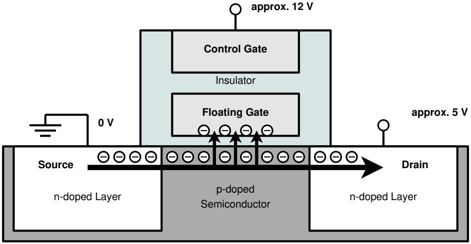
- A positively doped (p) semiconductor separates the 2 negatively doped (n) electrodes drain and source
  - Equal to a npn transistor, the npn passage is not conductive without a base current



- 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**



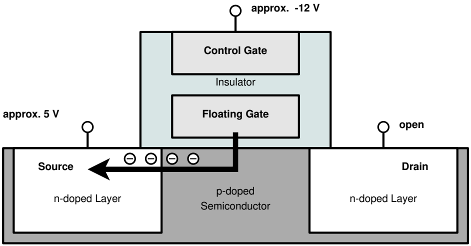
- A positive voltage (5V) is applied to the control gate
  - As a result, electrons can flow between source and drain
- If the high positive voltage is sufficiently high (6 to 20V), some electrons are tunneled ($\Longrightarrow$ Fowler-Nordheim tunneling) through the insulator into the floating gate
- 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
    $\Longrightarrow$ Write and erase operations are more complex than read operations
  - If data in a page needs 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

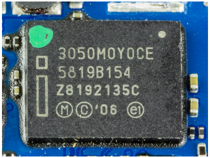
This influences the capacity and access time (latency)

NOR Memory

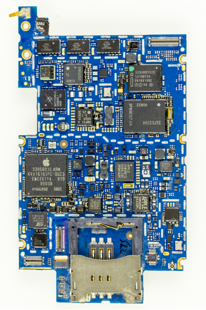
- Each memory cell has its own data line
  - Benefit:
    - Random access for read and write operations
      $\Longrightarrow$ Better latency compared with NAND memory
  - Drawback:
    - More complex ($\Longrightarrow$ expensive) construction
    - Higher power consumption than NAND memory
    - Typically small capacities ($\leq$ 32 MB)
- Does not contain pages
  - The memory cells are grouped together into 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



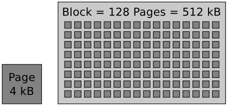
NOR flash memory (top image) on the IPhone 3G mainboard (bottom image)



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

NAND Memory

- The memory cells are grouped into pages
  - Typical page size: 512-8192 bytes
    - Each page has its own data line
  - Each block consists of a number of pages
    - Typical block sizes: 32, 64, 128 or 256 pages
- Benefit:
  - Lesser data lines $\Longrightarrow$ requires $<$ 50% of the surface area of NOR memory
  - Lower manufacturing costs compared with NOR flash memory
- Drawback:
  - No random access $\Longrightarrow$ 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

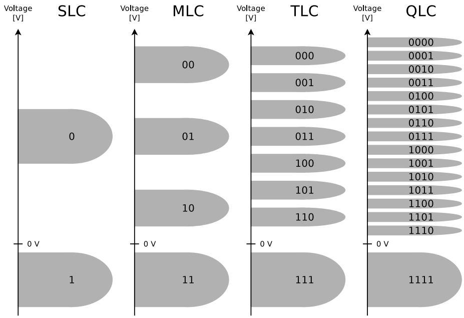


Fields of application

USB flash memory drives, SSDs, memory cards

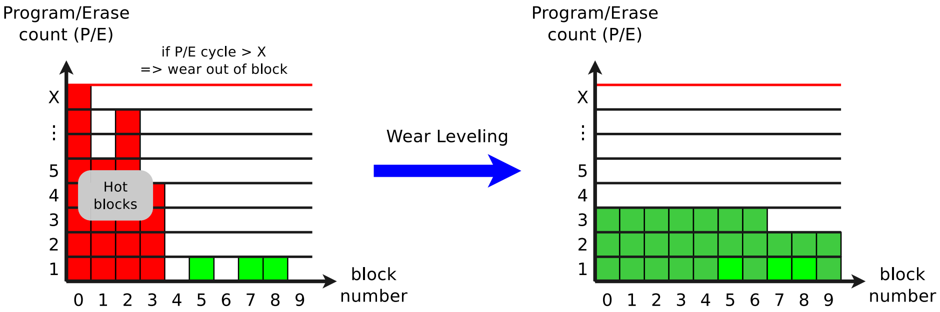
Single/Multi/Triple/Quad-Level Cell

- 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



- 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 WD30EZRSDTL, 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 $\leq 1\,\mu s \Longrightarrow \approx$ factor 100 better than HDDs
  - But the gap grows because of interface limitations and multiple CPU cores
- Further challenge
  - Storage drives can fail $\Longrightarrow$ risk of data loss
- Enhance **latency** and **reliability** of HDDs and SSDs $\Longrightarrow$ **RAID**

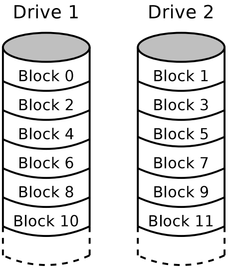
Redundant Array of independent Disks (RAID)

- The performance of the HDDs cannot 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 of 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

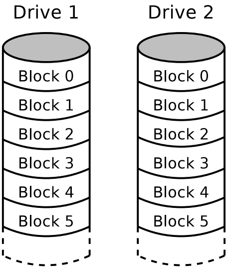
- No redundancy
  - Increases only the data rate
- Drives are partitioned into blocks of equal size
- If read/write operations are big enough (> 4 or 8 kB), the operations can be carried out in parallel on multiple drives or on all drives



- 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

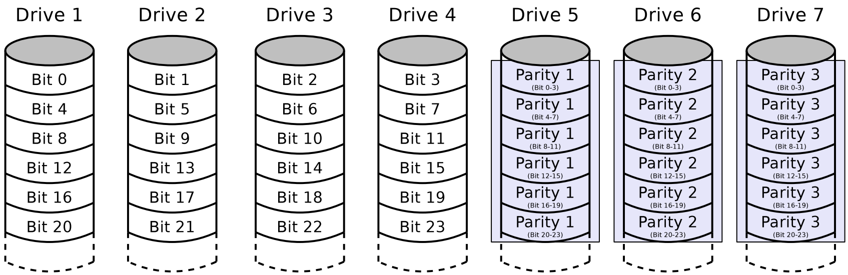
- At least 2 drives of the same capacity store identical data
  - If the drives are of different sizes, RAID 1 provides only the capacity of the smallest drive
- Failure of a single drive does not cause any data loss
  - Reason: The remaining drives store the identical data
- A total loss occurs only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

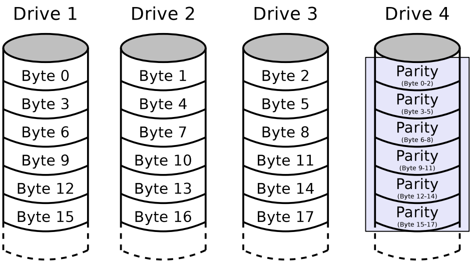
- Each sequential bit is stored on a different drive
  - Bits, which are powers of 2 (1, 2, 4, 8, 16, etc.) are parity bits



- The individual parity bits are distributed over multiple drives
  $\Longrightarrow$ 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

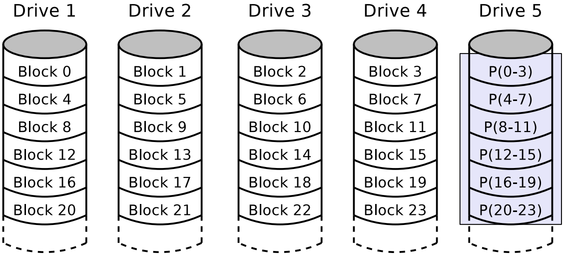


- Each write operation on the RAID causes write operations on the dedicated parity drive $\Longrightarrow$ bottleneck
- Was replaced by RAID 5

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



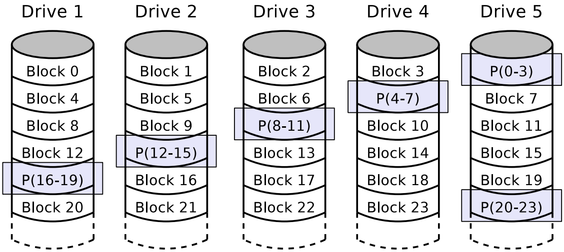
P(16-19) = Block 16 XOR Block 17 XOR Block 18 XOR Block 19

- 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

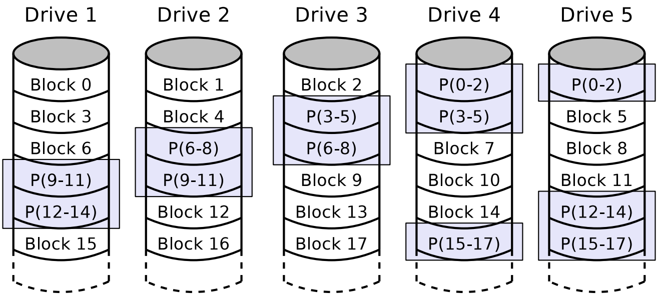
- Payload and parity information are distributed to all drives
- Benefits:
  - High throughput
  - High security level against data loss
  - No bottleneck



P(16-19) = 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. . .
  - the availability is better, but the write performance is lower
  - the effort to write the parity information is higher



Summary of the RAID Levels

If you want...

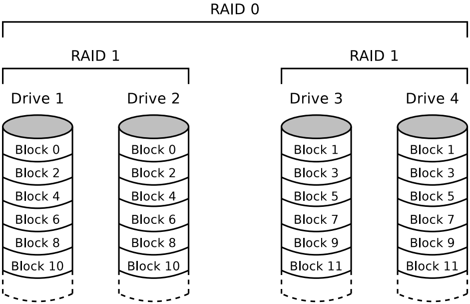
the best performance and don't care about availability $\Longrightarrow$ RAID 0
the best availability and don't care about performance $\Longrightarrow$ RAID 1
a combination of performance and availability $\Longrightarrow$ RAID 5 or RAID 6

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

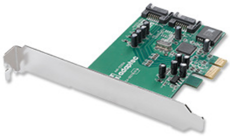
Examples

- 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



Adaptec SATA II RAID 1220SA

- **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)

- **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
```