Storage: HDD, SSD and RAID

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Give me two reasons why we would like to have secondary storage?
Computer architecture

Gigabyte Z170 Gaming

- 2 PCIe x16/x4
- 4 PCIe x1
- 2 USB 3.1
- 6 USB 3.0
- 4 USB 2.0
- 6 SATA-III
- 2 SATA Express
- 1 M.2
- 1 gigabit Ethernet
- 4 DDR4 SDRAM
Computer architecture

- **GPU**
  - PCIe x16 up to 128Gb/s

- **SDRAM**
  - Memory bus up to 160 Gb/s

- **CPU**
  - Memory bus up to 160 Gb/s
  - Memory access time < 1 ns

- **Control Hub**
  - PCIe x4
  - USB up to 10Gb/s
  - SATA up to 6Gb/s
  - SAS up to 12Gb/s
  - BIOS
  - Keyboard
  - Audio
  - Network

- **BIOS**

- **Keyboard**

- **Audio**

- **Network**

- **< 1 ns**

- **< 10 ns**

- **10 µs - 10 ms**
70 percent of the code of an operating system is code for device drivers.
how to interact with a device

- A register to read the status of the device.
- A register to instruct the device to read or write.
- A register that holds the data.
- I/O-bus could be separate from memory bus (or the same).
- The driver will use either special I/O instructions or regular load/store instructions.
char read_from_device() {

    while(STATUS == BUSY) {} // do nothing, just wait

    COMMAND = READ;

    while(STATUS == BUSY) {} // do nothing, just wait

    return DATA;

}
asynchronous I/O and interrupts

```c
int read_request(int pid, char *buffer) {

    while (STATUS == BUSY) {}  

    COMMAND = READ;
    interrupt->process = pid;
    interrupt->buffer = buffer;
    block_process(pid);
    scheduler();
}
```
asynchronous I/O and interrupts

```c
int interrupt_handler() {
    int pid = interrupt->pid;
    *(interrupt->buffer) = DATA;
    ready_process(pid);
}

This is very schematic, more complicated in real life.
```
process state

The kernel is interrupt driven.
Direct Memory Access

Allow devices to read and write to buffers in physical memory.

```c
int write_request(int pid, char *string, int size) {

    while(STATUS == BUSY) {} 

    memcpy(string, buffer, size)

    COMMAND = WRITE;

    blocked->pid = pid;

    block_process(pid);

    scheduler();
}
```
Each physical device is controlled by a *device driver* that provides the abstraction of a *character device* or *block device*.

Block devices used as interface to disk drives that provide persistent storage.

All though all storage devices are presented using the same abstraction, they have very different characteristics.

*To understand the challenges and options of the operating system, you should know the basics of how storage devices work.*
Anatomy of a HDD

- track/cylinder
- sectors per track varies
- sector size: 4K or 512 bytes
- platters: 1 to 6
- heads: one side or two sides

Only one head at a time is used (no parallel read).
Sector addressing

- Historically sectors address by cylinder-head-sector (CHS), due to incompatible standards the limitation was:
  - cylinder: 1024 (10-bits)
  - heads: 16 (4-bits)
  - sectors per cylinder: 63 (6-bits)
  - number of sectors: 1 Mi
  - largest disk assuming 512 Byte sectors: 512 MiByte

- Today, sectors are addresses linearly 0..n, Linear Block Addressing (LBA):
  - 28-bit or 48-bit address
  - up to 256 Ti sectors
  - largest disk assuming 4 KiByte sectors: 1 PiByte

> sudo hdparm -I /dev/sda
> dmesg | grep ata2
Seagate Desktop

- total capacity: 2 TiByte
- form factor: 3.5"
- rotational speed: 7.200 rpm
- connection: SATA III
- cache size: 64 MiByte
- read throughput: 156 MByte/s

aprx price, October 2016, 900:-
Seagate Cheetah 15K

- total capacity: 600 GiByte
- form factor: 3.5"  
- rotational speed: 15,000 rpm
- connection: SAS-3
- cache size: 16 MiByte
- read throughput: 204 MByte/s

aprx price, October 2016, 2.200:-
access time

- **seek time**: time to move arm to the right cylinder
- **rotation time**: time to rotate the disk
- **read time**: read one or more sectors
HDD - shoot out

- **Seagate Desktop**
  - rotation speed: 7200 rpm
  - average seek time: < 10 ms
  - average rotation time: 4 ms
  - average time to read a sector: < 14ms
  - capacity: 2 TiByte
  - aprx. price: 900:-
  - cost capacity: 0.44 SEK/GiByte

- **Seagate Cheeta 15K**
  - rotation speed: 15000 rpm
  - average seek time: < 4 ms
  - average rotation time: 2 ms
  - average time to read a sector: < 6ms
  - capacity: 600 GiByte
  - aprx. price: 2.200:-
  - cost capacity: 3.70 SEK/GiByte
If a sector is 512 bytes, it takes 10ms to find and read a sector, and we want to read 512 MiBytes then .....?

- Time to find first sector is less relevant.
- If sectors that belong to the same file are close to each other we minimize movement of arm.
- Rotational speed should be high.
- The density i.e. how many sectors in each track is important.
- The communication with the drive should be fast.
- Typical read and write performance is between 150 MiByte/s to 250 MiByte/s.
Historically, the Operating System was in complete control:

- it knew the layout cylinder-head-sector (CHS),
- could order data in segments that were close to each other and,
- would schedule disk operations to minimize arm movement.

Today, the drive can often make a better decision:

- it knows, but might not reveal, the layout.
- The operating system can help in grouping operations together, allowing the drive to decide in what order they should be done (Native Command Queuing).

*There is a reason why MS-DOS is called MS-DOS.*
SSD - Solid State Drive

Samsung 850 EVO

- total capacity: 250 GiByte
- form factor: 2.5"
- connection: SATA III
- cache size: 64 MiByte
- random access: 30 $\mu$s
- read throughput: 540 MiByte/s

*aprx price, October 2018, 685:-*
SanDisk Ultra SDXC

- form factor: SDXC
- capacity: 64 GiByte
- read performance: 80 MiByte/s

aprx price, October 2016, 300:-
NAND - flash storage

You have constant time access to any page.
You can only write to (or program) an erased page.
You can only erase a block.
### Price Performance

<table>
<thead>
<tr>
<th>Drive</th>
<th>Capacity</th>
<th>Price</th>
<th>SEK/GiByte</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDD Desktop</td>
<td>2 TiByte</td>
<td>900:-</td>
<td>44 öre</td>
</tr>
<tr>
<td>HDD Performance</td>
<td>600 GiByte</td>
<td>2.200:-</td>
<td>3.70:-</td>
</tr>
<tr>
<td>SSD Desktop</td>
<td>250 GiByte</td>
<td>685:-</td>
<td>2.75:-</td>
</tr>
</tbody>
</table>

*2016 figures: SSD 4:-/GiByte*
SSHD - Hybrid SSD/HDD

Seagate Firecuda - SSHD

- total capacity: 2 TiByte
- form factor: 3.5"
- rotational speed: 7.200 rpm
- connection: SATA-III
- SSD cache: 8 GiByte
- cache size: 64 MiByte
- read throughput: 210 MByte/s

Seagate Firecuda SSHD, aprx price, November 2018, 1.200:-
Bus limitations

- SATA-III - 6 Gb/s, most internal HDD and SSD today
- SAS-3 - 12 Gb/s, enterprise RAID HDD
- USB3.1 - 10 Gb/s, everything
- PCI Express 3.0 x16 - 128 Gb/s, what is it used for?

An SSD has a read throughput of 500 MiByte/s which is a .... b/s?
SSD on the PCIe bus

Corsair Neutron NX500

- total capacity: 400 GiByte
- connection: PCI Express 3.0 x4
- read performance: 3000 MByte/s
- write performance: 2400 MByte/s

aprx price, November 2019, 3.399:-

2016 October, Intel SSD 400 GB, 4.599:-
The M.2 connector

Samsung 960 PRO 512GB

- total capacity: 512 GiByte
- form factor: M.2-
- connection: PCI Express 3.0 x4
- read performance: 3.500 MByte/s
- write performance: 2.100 MByte/s

aprx price, November 2018, 2.890:-
aprx price, November 2019, 1.890:-
SSD on the memory bus

HP NVDIMM 8GB

- regular DRAM backed up by Flash
- total capacity: 16 GiByte
- form factor: DDR4 SDIM
- bus speed: 2666 MT/s

aprx price, November 2018, 7.600:-
Yes!

Intel Optane DC NVDIMM 512GB

- total capacity: 512 GiByte
- price: 7.900 USD
Increase capacity, performance and/or reliability

Redundant Array of Independent Disks
RAID

- Multiple disks that can provide:
  - capacity: looks like a 20 TiByte disk but is actually 10 2TiByte disks
  - performance: spread a file across ten drives, read and write in parallel
  - reliability: write the same file to several disks, if one crashes - not a problem
Alternatives:

- The cabinet that holds the disks present itself as one drive.
- A device driver in the kernel knows that we have several disks but the kernel presents it as one disk to the application layer.
- The application layer knows that we have several disks but provides a API to other applications that looks a single drive.
RAID levels

- RAID 0: *stripe* files across several drives.
- RAID 1: keep a complete *mirror copy* of each file.
- RAID 2-6: spread a file plus parity information across several drives.
Summary

application layer, simple to understand

system calls: open, read, write, lseek ...

all devices have a generic API
device drivers that know what they are doing

now it’s a bit structured
I/O and memory buses, protocols suchs as SATA, SCSI, USB etc

hardware - a complete mess