Storage: HDD, SSD and RAID

Johan Montelius

KTH

2017
Why?

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

CPU
Computer architecture

CPU

SDRAM

memory bus up to 160 Gb/s
Computer architecture

CPU

SDRAM

memory bus up to 160 Gb/s

GPU

PCIe x16 up to 128Gb/s
Computer architecture

**CPU**
- PCIe x16 up to 128 Gb/s
- PCIe x4
- Memory bus up to 160 Gb/s

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

**Control Hub**
- USB up to 10 Gb/s
- SATA up to 6 Gb/s
- SAS up to 12 Gb/s

**SDRAM**
Computer architecture

- **CPU**
  - SDRAM memory bus up to 160 Gb/s
  - PCIe x16 up to 128 Gb/s

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

- **Control Hub**
  - USB up to 10 Gb/s
  - SATA up to 6 Gb/s
  - SAS up to 12 Gb/s
  - PCIe x4
  - BIOS
  - keyboard
  - audio
  - network
Computer architecture

- **GPU**: PCIe x16 up to 128Gb/s
- **CPU**: Memory bus up to 160 Gb/s
- **SDRAM**: PCIe x16 up to 128Gb/s
- **Control Hub**: USB up to 10Gb/s, SATA up to 6Gb/s, SAS up to 12Gb/s
- **BIOS**, **keyboard**, **audio**, **network**
Computer architecture

- GPU: PCIe x16 up to 128Gb/s
- CPU: < 1 ns
- SDRAM: < 10 ns
- Control Hub:
  - USB up to 10Gb/s
  - SATA up to 6Gb/s
  - SAS up to 12Gb/s
- BIOS, keyboard, audio, network

Memory bus:
- PCIe x16 up to 160 Gb/s
Computer architecture

- **CPU**
  - PCIe x16 up to 128 Gb/s
  - PCIe x4
  - Memory bus up to 160 Gb/s

- **Control Hub**
  - USB up to 10 Gb/s
  - SATA up to 6 Gb/s
  - SAS up to 12 Gb/s

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

- **SDRAM**
  - < 10 ns

- **BIOS**
  - 10 μs - 10 ms

- **Keyboard**
- **Audio**
- **Network**
70 percent of the code of an operating system is code for device drivers.
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System architecture

application

POSIX API

I/O library

OS

kernel space

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how to interact with a device

- driver
- 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.
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status

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- 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;

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    return DATA;
};
int read_request(int pid, char *buffer) {

    while (STATUS == BUSY) {} 

    COMMAND = READ;

    interrupt -> process = pid;
    interrupt -> buffer = buffer;

    block_process(pid);

    scheduler();
}
int interrupt_handler() {
    int pid = interrupt->pid;
    *(interrupt->buffer) = DATA;
    ready_process(pid);
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This is very schematic, more complicated in real life.`
The kernel is interrupt driven.
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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) {} // BLOCK
    memcpy (string, buffer, size)
    COMMAND = WRITE;
    blocked -> pid = pid;
    block_process (pid);
    scheduler();
}
```

DMA often limited to lower memory addresses.
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Direct Memory Access

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*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).
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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 addressed 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
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> sudo hdparm -I /dev/sda
> dmesg | grep ata2
Seagate Desktop

HDD - Hard Disk Drive

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

ST2000DM001, aprx price, October 2016, 900:-
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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

ST3300657SS, aprx price, October 2016, 2.200:-
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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
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- 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: < 14 ms
  - Capacity: 2 TiByte
  - Approx. 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: < 6 ms
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- 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.
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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).
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- random access: 30 $\mu$s

MZ-75E250B/EU, aprx price, October 2016, 1000:-
Samsung 850 EVO

- total capacity: 250 GiByte
- form factor: 2.5"
- connection: SATA III
- cache size: 64 MiByte
- random access: 30 $\mu$s
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MZ-75E250B/EU, aprx price, October 2016, 1000:-
SanDisk Ultra SDXC

- form factor: SDXC
- capacity: 64 GiByte
- read performance: 80 MiByte/s
- approximate price, October 2016: 300:-
SanDisk Ultra SDXC

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

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erase blocks ~256 KiByte
NAND - flash storage

- Memory bank
- Erase blocks ~256 KiByte
- Pages ~4 KiByte
NAND - flash storage

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memory bank

erase blocks \(\sim 256\) KiByte

pages \(\sim 4\) KiByte
NAND - flash storage

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You can only write to (or program) an erased page.
NAND - flash storage

You have constant time access to any page.
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You can only erase a block.
<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>1000:-</td>
<td>4:-</td>
</tr>
</tbody>
</table>
SATA-III - 6 Gb/s, most internal HDD and SSD today
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SAS-3 - 12 Gb/s, enterprise RAID HDD
Bus limitations

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

Intel SSD 750 Series

- total capacity: 400 GiByte
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Intel SSD 750 Series

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- read performance: 2200 MByte/s
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*apr* price, *October 2016*, 4.599:-
The M.2 connector

Samsung 960 EVO 500GB

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The M.2 connector

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aprx price, November 2017, 2.400:-
SSD on the memory bus

HP NVDIMM 8GB
SSD on the memory bus

HP NVDIMM 8GB

- regular DRAM backed up by Flash
SSD on the memory bus

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- total capacity: 8 GiByte

aprx price, October 2016, ???
SSD on the memory bus

HP NVDIMM 8GB

- regular DRAM backed up by Flash
- total capacity: 8 GiByte
- form factor: DDR4 SDIM
SSD on the memory bus

HP NVDIMM 8GB

- regular DRAM backed up by Flash
- total capacity: 8 GiByte
- form factor: DDR4 SDIM
- bus speed: 2133 MHz

aprx price, October 2016, ???
Next year?

Intel Optane - 3D XPoint NVDIMM
Next year?

Intel Optane - 3D XPoint NVDIMM

in the pipe line
Next year?

Intel Optane - 3D XPoint NVDIMM

- in the pipeline
- total capacity: 512 GiByte
Next year?

Intel Optane - 3D XPoint NVDIMM

- in the pipeline
- total capacity: 512 GiByte
Increase capacity, performance and/or reliability

Redundant Array of Independent Disks
RAID
Increase capacity, performance and/or reliability

Redundant Array of Independent Disks
RAID

- Multiple disks that can provide:
Increase capacity, performance and/or reliability

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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:
Alternatives:

- The cabinet that holds the disks present itself as one drive.
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- A device driver in the kernel knows that we have several disks but the kernel presents it as one disk to the application layer.
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- 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 0: *stripe* files across several drives.
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- RAID 1: keep a complete *mirror copy* of each file.
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

hardware - a complete mess
Summary

application layer, simple to understand

I/O and memory buses, protocols such as SATA, SCSI, USB etc

hardware - a complete mess
application layer, simple to understand

now it’s a bit structured
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Summary

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device drivers that know what they are doing

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application layer, simple to understand

- 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 such as SATA, SCSI, USB etc

hardware - a complete mess
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