Storage: HDD, SSD and RAID

Johan Montelius

KTH

2018
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
CPU

SDRAM

memory bus up to 160 Gb/s
Computer architecture

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

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

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

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

- **SDRAM**
Computer architecture

- **CPU**
  - SDRAM: memory bus up to 160 Gb/s
  - PCIe x16: up to 128 Gb/s
  - PCIe x4

- **Control Hub**
  - BIOS
  - Keyboard
  - Audio
  - Network

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

- **SDRAM**
  - SATA: up to 6 Gb/s
  - SAS: up to 12 Gb/s
  - USB: up to 10 Gb/s
Computer architecture

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

- **GPU**

- **SDRAM**

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

- **BIOS**
- **Keyboard**
- **Audio**
- **Network**

< 1 ns
Computer architecture

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

- **SDRAM**
  - < 10 ns

- **Control Hub**
  - PCIe x4
  - 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

- **BIOS**
  - Keyboard
  - Audio
  - Network
Computer architecture

- **GPU**: PCIe x16 up to 128 Gb/s
- **SDRAM**: memory bus up to 160 Gb/s
- **CPU**: < 1 ns
- **Control Hub**: PCIe x4
- **BIOS**
- **Keyboard**
- **Audio**
- **Network**
- **USB**: up to 10 Gb/s
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Timing:
- < 1 ns
- < 10 ns
- 10 µs - 10 ms
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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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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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The kernel is interrupt driven.
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Direct Memory Access

Allow devices to read and write to buffers in physical memory.
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```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();
}
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DMA often limited to lower memory addresses.
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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

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

HDD - Hard Disk Drive

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:-
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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
aprx price, October 2016, 2.200:-
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aprx price, October 2016, 2.200:-
access time
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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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- read time: read one or more sectors
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  - 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
  - Capacity: 600 GiByte
  - Approx. price: 2.200:-
  - Cost capacity: 3.70 SEK/GiByte
HDD - shoot out

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read/write performance

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- 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:

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- 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.
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SSD - Solid State Drive

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*aprx price, October 2018, 685:*
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- connection: SATA III
- cache size: 64 MiByte
- random access: 30 \( \mu \) s
- read throughput: 540 MiByte/s
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aprx price, October 2018, 685:-
SanDisk Ultra SDXC

- form factor: SDXC
- capacity: 64 GiByte
- read performance: 80 MiByte/s
- approx price, October 2016, 300:-
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SD cards - flash memory

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

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memory bank

erase blocks ~256 KiByte
NAND - flash storage

- memory bank
- erase blocks ~256 KiByte
- pages ~4 KiByte
NAND - flash storage

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<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>
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</tr>
<tr>
<td>Drive</td>
<td>Capacity</td>
<td>Price</td>
<td>SEK/GiByte</td>
</tr>
<tr>
<td>-------------------</td>
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<td>------------</td>
</tr>
<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>
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</tbody>
</table>

2016 figures: SSD 4:-/GiByte
Seagate Firecuda - SSHD

- Total capacity: 2 TiByte
- Form factor: 3.5" (3.5 inch)
- 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:-
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SSHHD - Hybrid SSD/HDD

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*Seagate Firecuda SSHD, aprx price, November 2018, 1.200:-*
SATA-III - 6 Gb/s, most internal HDD and SSD today
Bus limitations

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Bus limitations

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An SSD has a read throughput of 500 MiByte/s which is a ... b/s?
Corsair Neutron NX500

- total capacity: 400 GiByte
SSD on the PCIe bus

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aprx price, November 2018, 3.599:-
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aprx price, November 2018, 3.599:-
2016 October, Intel SSD 400 GB, 4.599:-
The M.2 connector

Samsung 960 PRO 512GB

- total capacity: 512 GiByte
The M.2 connector

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The M.2 connector

Samsung 960 PRO 512GB

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- 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:-
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

HP NVDIMM 8GB

- regular DRAM backed up by Flash
- total capacity: 16 GiByte
SSD on the memory bus

HP NVDIMM 8GB

- regular DRAM backed up by Flash
- total capacity: 16 GiByte
- form factor: DDR4 SDIM
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:-
Next year?

Intel Optane - 3D XPoint NVDIMM
Next year?

Intel Optane - 3D XPoint NVDIMM

*in the pipeline*
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 Independet 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
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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 levels

- RAID 0: *stripe* files across several drives.
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- RAID 1: keep a complete *mirror copy* of each file.
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- 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
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now it's a bit structured
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application layer, simple to understand

all devices have a generic API
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now it’s a bit structured
I/O and memory buses, protocols suchs 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