Mass-Storage Structure

DM510 Operating Systems

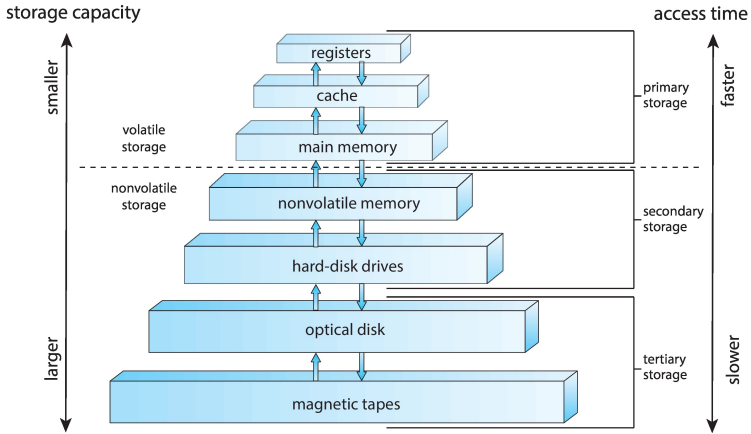
Lars Rohwedder

Disclaimer

These slides contain (modified) content and media from the official Operating System Concepts slides:
https://www.os-book.com/OS10/slide-dir/index.html

Today's lecture

> Chapter 11 of course book, concerning non-volatile storage:

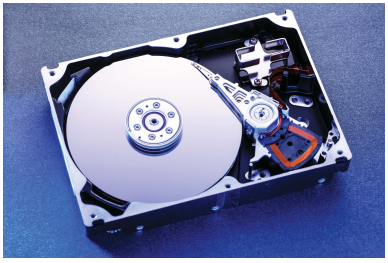


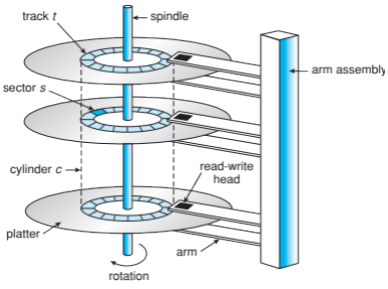
Hardware

Hard disk drives (HDD)

Has been the standard storage device in computing for a long time

- Several **platters** spin under a **read-write head**
- Each platter has **tracks**. Each track has sectors. Head can move between **cylinders**, which are tracks of all platters with the same location
- **Transfer rate:** rate at which data is transferred between HDD and main memory
- **Positioning time (random-access time):** time to move head to correct cylinder (**seek time**) and time to move sector under head (**rotational latency**)
- Moving parts lead to a higher risk of permanent damage, for example, from a **head crash** (collision of head with disk)





HDD performance

Typical speeds

Actual numbers vary between products

- **Total storage:** 30 GB $- 3$ TB
- **Transfer rate:** $0.1 - 1$ GB/s
- **Average seek time:** $3 - 9$ ms
- **Average rotational latency:** $2 - 6$ ms $(= 1/2 \cdot 1/\mathrm{RPM})$

$$\text{average access time} = \text{average seek time} + \text{average rotational latency}$$

$$\text{average I/O time} = \text{average access time} + \frac{\text{amount to transfer}}{\text{transfer rate}} + \text{controller overhead}$$

HDD performance

Typical speeds

Actual numbers vary between products

- **Total storage:** 30 GB $-$ 3 TB
- **Transfer rate:** $0.1 - 1$ GB/s
- **Average seek time:** $3 - 9$ ms
- **Average rotational latency:** $2 - 6$ ms $(= 1/2 \cdot 1/\mathrm{RPM})$

$$\text{average access time} = \text{average seek time} + \text{average rotational latency}$$

$$\text{average I/O time} = \text{average access time} + \frac{\text{amount to transfer}}{\text{transfer rate}} + \text{controller overhead}$$

Example (blackboard)

Transfer block of 4 KB, 7200 RPM, 5 ms average seek time, 0.1 GB/s transfer rate, 0.1 ms controller overhead

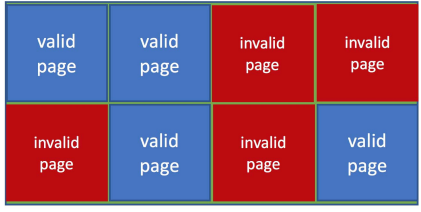
Nonvolatile memory devices (NVM)

NVMs includes SSDs, USB drives, and SD cards. They gain popularity as primary storage device recently

- No moving parts ⇝ more reliable, no seek time or rotational latency
- Comparison to HDD: more expensive (per MB), lower capacity, faster random access
- Limited number of write cycles ⇝ potentially shorter life span than HDD, but more predictable

Writing to NVM

- Cannot overwrite a page (similar to sector) in place, instead data is relocated and old page is invalidated
- Once block (of multiple pages) is mostly invalid, entire block is erased and can be reused
- Number of times a block can be erased is limited ($\approx 100000\times$)
  $\rightsquigarrow$ device controller should ensure different blocks are worn out evenly



Tertiary storage

Magnetic tapes

- Tape needs to be wound or rewound past read-write head. Moving to correct position can take minutes
- Similar transfer rates to HDD and large capacities (e.g. > 100 TB)
- Mainly for used for backup nowadays (tertiary storage)

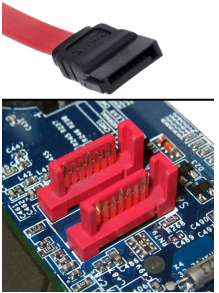
Optical disks

- CD-ROM, CD-RW, DVD
- Sometimes, but not always rewritable
- Suitable for backup (tertiary storage)

Interface with storage devices

Storage device I/O

- Storage devices appear as arrays of logical blocks numbered $1, 2, \ldots, n$
- For HDDs, logical blocks are mapped to physical locations in natural way: first block to first track of outermost cylinder, then next blocks follow sequentially until end of track. Afterwards, next track, next cylinder, etc.
  $\rightsquigarrow$ **proximity in logical address $\approx$ proximity in cylinder, section, etc.**
- HDD connected via specialised bus, e.g. SATA
- Due to higher speed, SSDs are often connected directly to PCI bus, via NVM express
- Device controller manages disk, writes and reads from main memory via direct memory access (DMA), interacts with CPU via I/O requests and interrupts

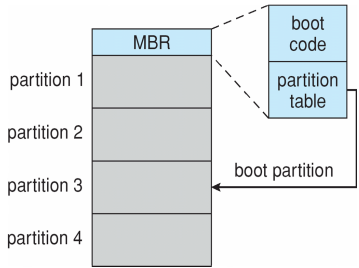


SATA port

Storage device management

Data structure on disk

- Storage devices are divided into **partitions** (for HDDs a partition typically comprises a subset of cylinders)
- **Formatting** creates a **file system** on a partition
- Roles of partitions: boot partition (containing bootloader), swap space (for use in paging), root partition (contains file system with operating system), mountable file systems, raw partition (used by specialized applications such as databases)



Before storage device is accessible for user, file system on device must be **mounted**. File systems will be topic of the next lectures

HDD Scheduling

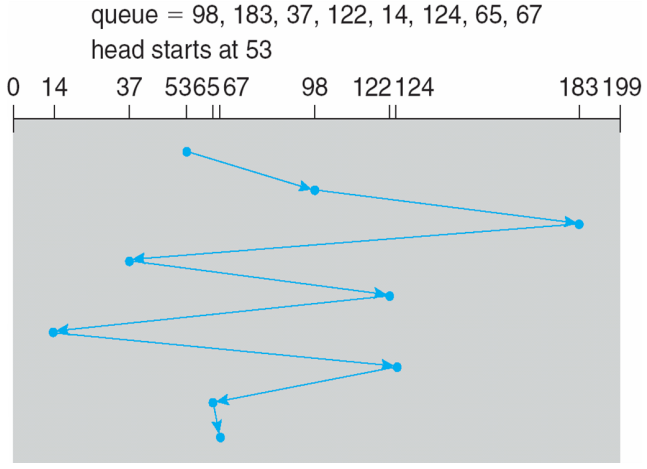
Overview

When a disk is under heavy load and requests queue up, the device controller implements scheduling algorithms and applies them to the queue. Goals:

- minimize overhead from seeking
- fairness between requests

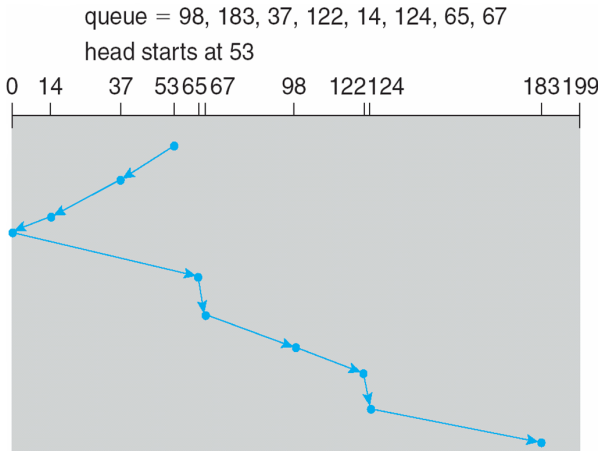
First-come-first-serve (FCFS)

- Requests are served in the order they arrive
- In example below the total movement is 640 cylinders



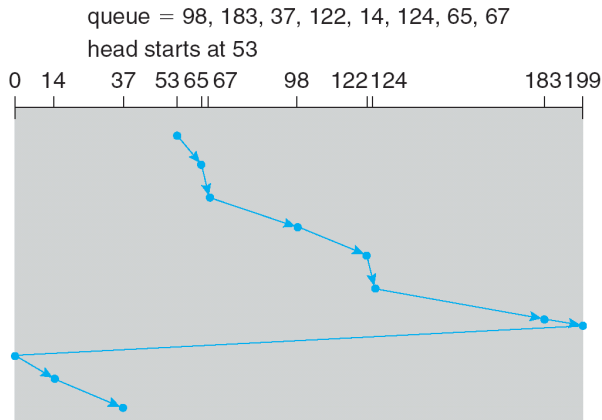
SCAN

- Starting at one end, head moves towards other end and services all requests on the way. Once the last request is reached, the direction is reversed
- In the example, the total movement is 208 cylinders
- Requests at either end tend to wait longer than those in the middle



C-SCAN

- Like SCAN, but when end is reached, move all the way to the beginning again
- In the example, the total movement is 383 cylinders
- Serves requests more uniformly than SCAN



Other scheduling algorithms

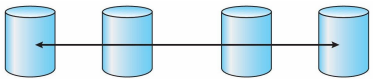
- Shortest-seek-time-first (SSTF): service request closest to current head position next
- Several queues for read and write: useful to give priority to reads because they are more likely to lead to blocking
- Several queues against starvation: use “unfair” algorithm on one queue, but move to a FCFS queue if request has not been served for too long

RAID

Redundant array of inexpensive disks (RAID)

RAID has two purposes:

- To protect against data loss, when disks fail permanently
- To increase performance via parallelism



Data striping

- Several physical disks are combined to one logical disk (of larger size)
- Example: the ith disk ($i = 1, 2, \ldots, n$) stores logical blocks $i, i + n, i + 2n, \ldots$
- Leads to load balancing:
  Large accesses: when we read $k \cdot n$ consecutive blocks, we only need to read k block from each disk $\rightsquigarrow$ up to $n\times$ higher throughput.
  Small accesses: single block accesses are distributed over disks

RAID levels

RAID 0

> No redundancy, failure always leads to data loss

(a) RAID 0: non-redundant striping.

RAID levels

RAID 0

- No redundancy, failure always leads to data loss

(a) RAID 0: non-redundant striping.

RAID 1

- Every disk is duplicated
- Can recover from single disk failure
- Requires $2\times$ more disks

(b) RAID 1: mirrored disks.

RAID levels

RAID 0

- No redundancy, failure always leads to data loss

(a) RAID 0: non-redundant striping.

RAID 1

- Every disk is duplicated
- Can recover from single disk failure
- Requires $2\times$ more disks

(b) RAID 1: mirrored disks.

RAID 4

- One extra disk that stores parity:

$$P[i] = D_1[i] + D_2[i] + D_3[i] + \cdots \mod 2$$

  where $D_1, D_2, D_3, \ldots$ are disks, P is additional parity disk, i indexes block of data of each disk
- Can also recover from single disk failure, but requires only one extra disk

(c) RAID 4: block-interleaved parity.

RAID levels (cont'd)

RAID 5

- like RAID 4, but for different blocks, different disks take role of parity
- more balanced accesses than RAID 4, where parity disk is accessed on every write

(d) RAID 5: block-interleaved distributed parity.

RAID levels (cont'd)

RAID 5

- like RAID 4, but for different blocks, different disks take role of parity
- more balanced accesses than RAID 4, where parity disk is accessed on every write

(d) RAID 5: block-interleaved distributed parity.

RAID 6

- Additional redundancy to be able to recover from multiple failures
- Details omitted

(e) RAID 6: P + Q redundancy.

RAID levels (cont'd)

RAID 5

- like RAID 4, but for different blocks, different disks take role of parity
- more balanced accesses than RAID 4, where parity disk is accessed on every write

(d) RAID 5: block-interleaved distributed parity.

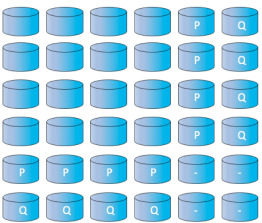
RAID 6

- Additional redundancy to be able to recover from multiple failures
- Details omitted

(e) RAID 6: P + Q redundancy.

Multidimensional RAID 6

- Disks (virtually) aligned in matrix, redundancy on each column and row
- Few additional disks, high failure tolerance



(f) Multidimensional RAID 6.

Mean time to data loss

We measure how likely data loss is in **mean time to data loss (MTTDL)**. To estimate it, the relevant parameters are:

- For each disk we are given **mean time to failure (MTTF)**: how much time passes on average until disk fails
- We are also given the **mean time to repair (MTTR)**: time until a broken disk is replaced

Under reasonable assumptions, the average time until two disks out of n identical disks fail simultaneously is well estimated by:

$$\mathrm{MTTDL} = \frac{\mathrm{MTTF}^2}{n(n-1) \cdot \mathrm{MTTR}}$$

Mean time to data loss

We measure how likely data loss is in **mean time to data loss (MTTDL)**. To estimate it, the relevant parameters are:

- For each disk we are given **mean time to failure (MTTF)**: how much time passes on average until disk fails
- We are also given the **mean time to repair (MTTR)**: time until a broken disk is replaced

Under reasonable assumptions, the average time until two disks out of n identical disks fail simultaneously is well estimated by:

$$\mathrm{MTTDL} = \frac{\mathrm{MTTF}^2}{n(n-1) \cdot \mathrm{MTTR}}$$

Example

- A single disk is mirrored with RAID 1
- Mean time to failure of each disk is $100000h \approx 11.4$ years
- Mean time to repair is 10 hours
- Then mean time to data loss $= \frac{100000^2}{2 \cdot 10} h = 500 \cdot 10^6 h \approx 57000$ years