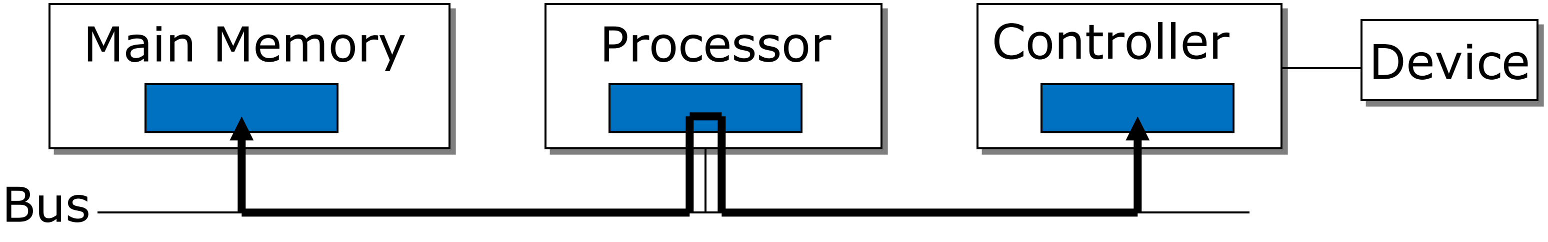
A supercomputer is a machine for turning a compute-bound problem into an I/O-bound problem.
- *Ken Batcher (US computer architect)*

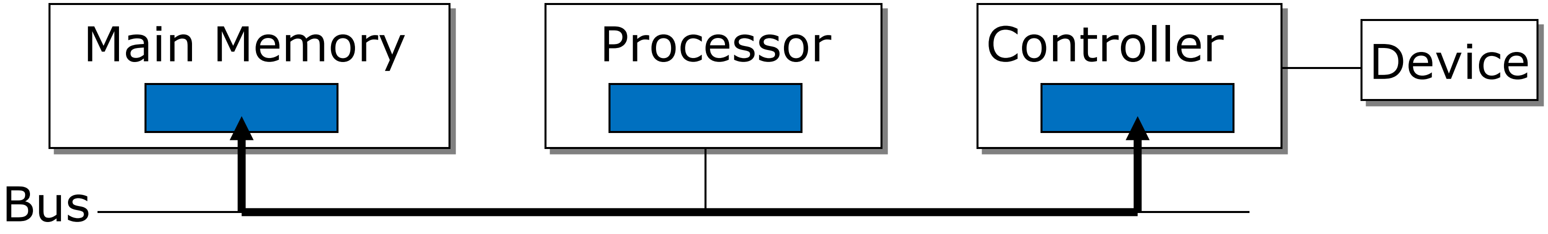
Chapter 8

I/O Devices

8.1 Input/Output Basics



Processor (programmed I/O)
The processor reads or writes data in bytes or words from/into a register in the controller.



Direct Memory Access (DMA)
The controller can autonomously access the memory via the bus.

Control

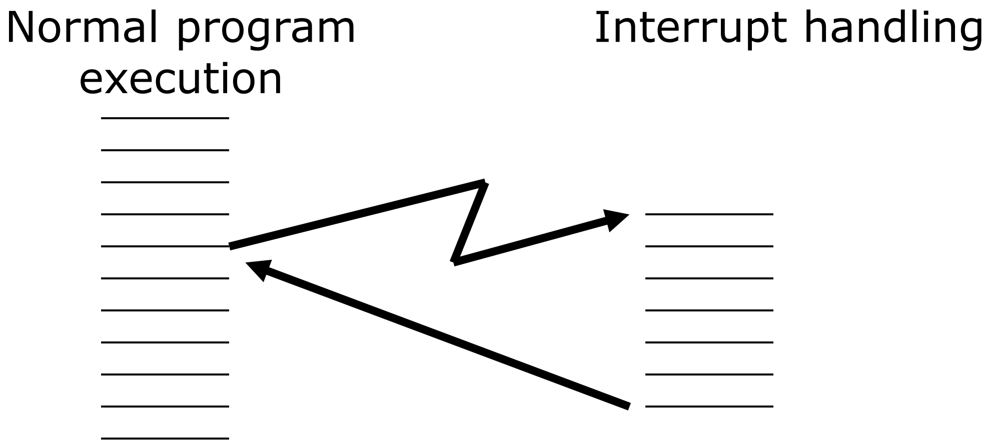
- **Triggering** (How does the controller get the requests?)

- The processor loads the corresponding register in the particular controller:
  - Type of operation (e.g. read, write)
  - Source
  - Target
  - Status

- **Reaction**
  - After completion of the I/O operation, the processor needs to be informed.
  - Two possibilities:
    - The processor checks occasionally the controller‘s status register (**Polling**). (In most cases too inefficient.)
    - The processor gets informed about the completion by a special signal (**Interrupt**). (Usual approach)

Interrupts

- There is at least one interrupt wire for the processor.
- After each instruction the processor checks whether there is a signal (corresponding voltage level) at this wire.
- If so, it immediately (if interrupts are enabled) jumps to a subroutine that evaluates the interrupt and performs or triggers the necessary actions.

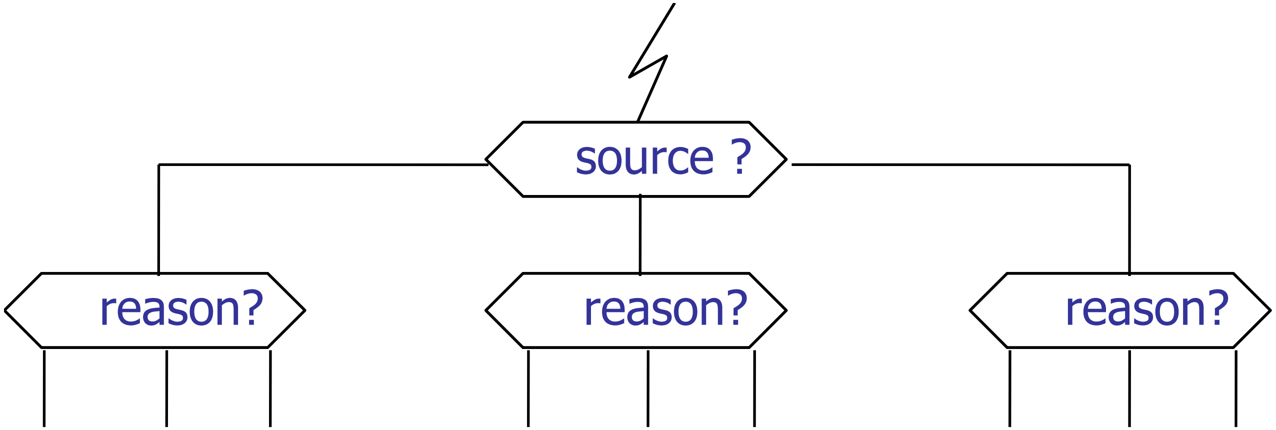


Interrupt analysis

- First, we only know the very fact of an interrupt.

- Therefore, we need to find out,
  who (which device) caused the interrupt (source),
  why the interrupt has happened (e.g. end of transmission, error).

- Thus, a subroutine for interrupt handling has the following structure:

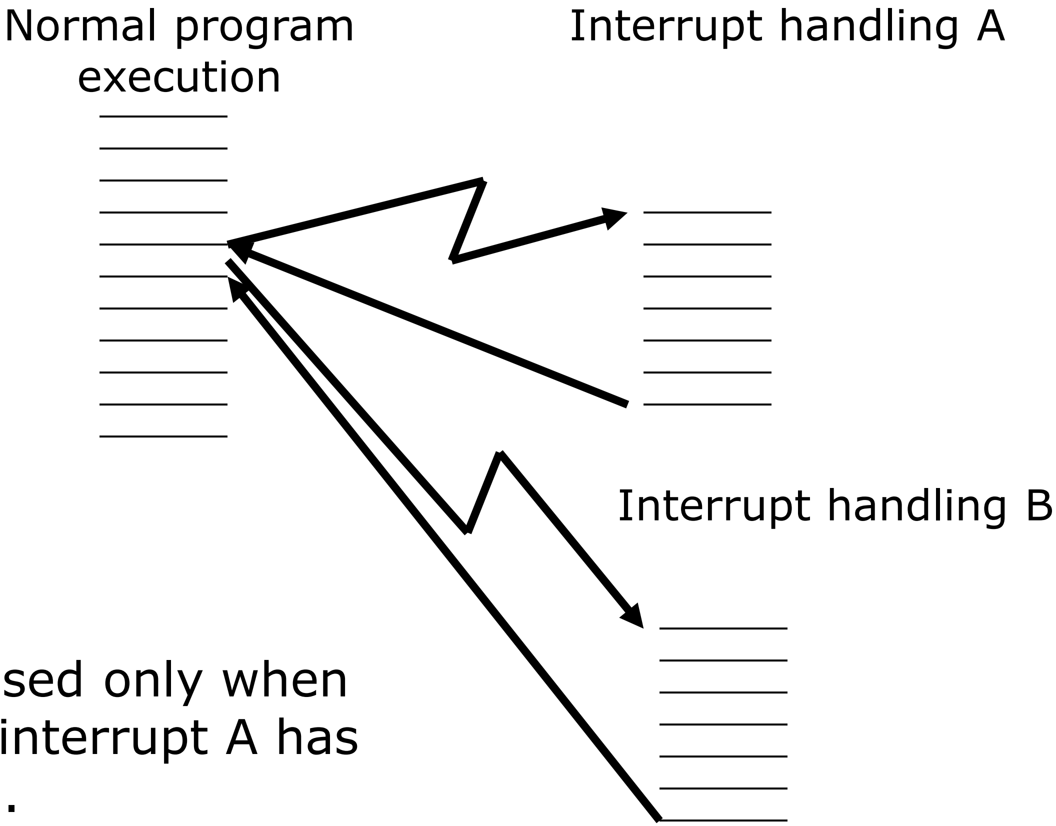


Interrupt processing

- An interrupt can occur at any time and in any situation.
- Especially also during an interrupt processing!
- Two approaches:
  - Sequential interrupt processing (FCFS)
  - Nested interrupt processing
- The interrupt mechanism is also used for processor internal (synchronous) events, at which we need immediate reaction (division by zero, address violation). In that case, it is usually called **exception**.

Sequential interrupt processing

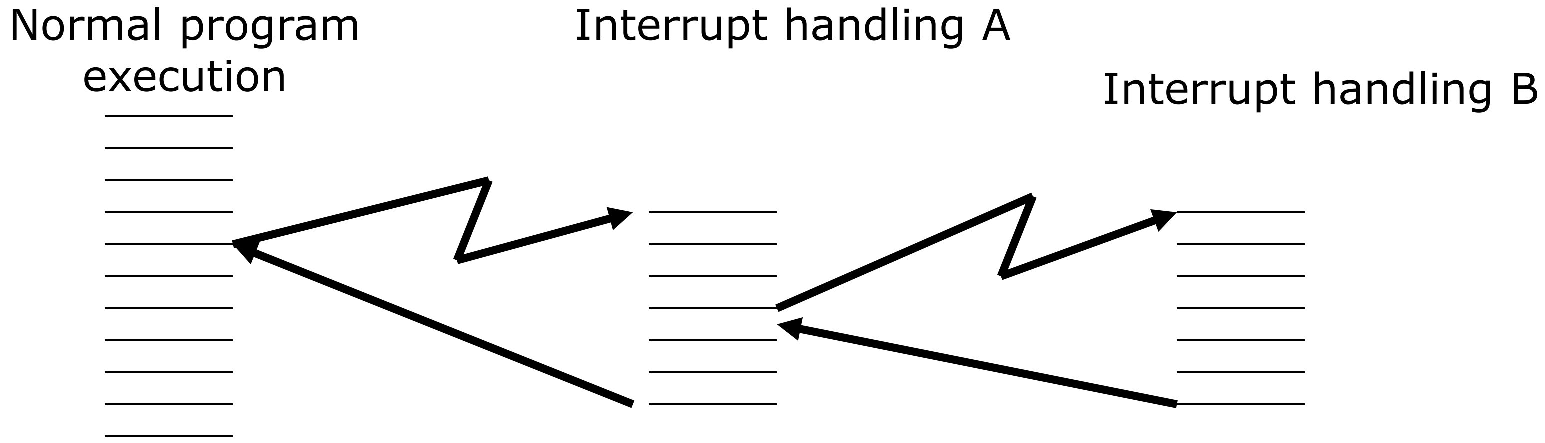
- Prevent further interrupts during interrupt processing (disable interrupt).
- The prevention can be limited to specific types of interrupts (masking).



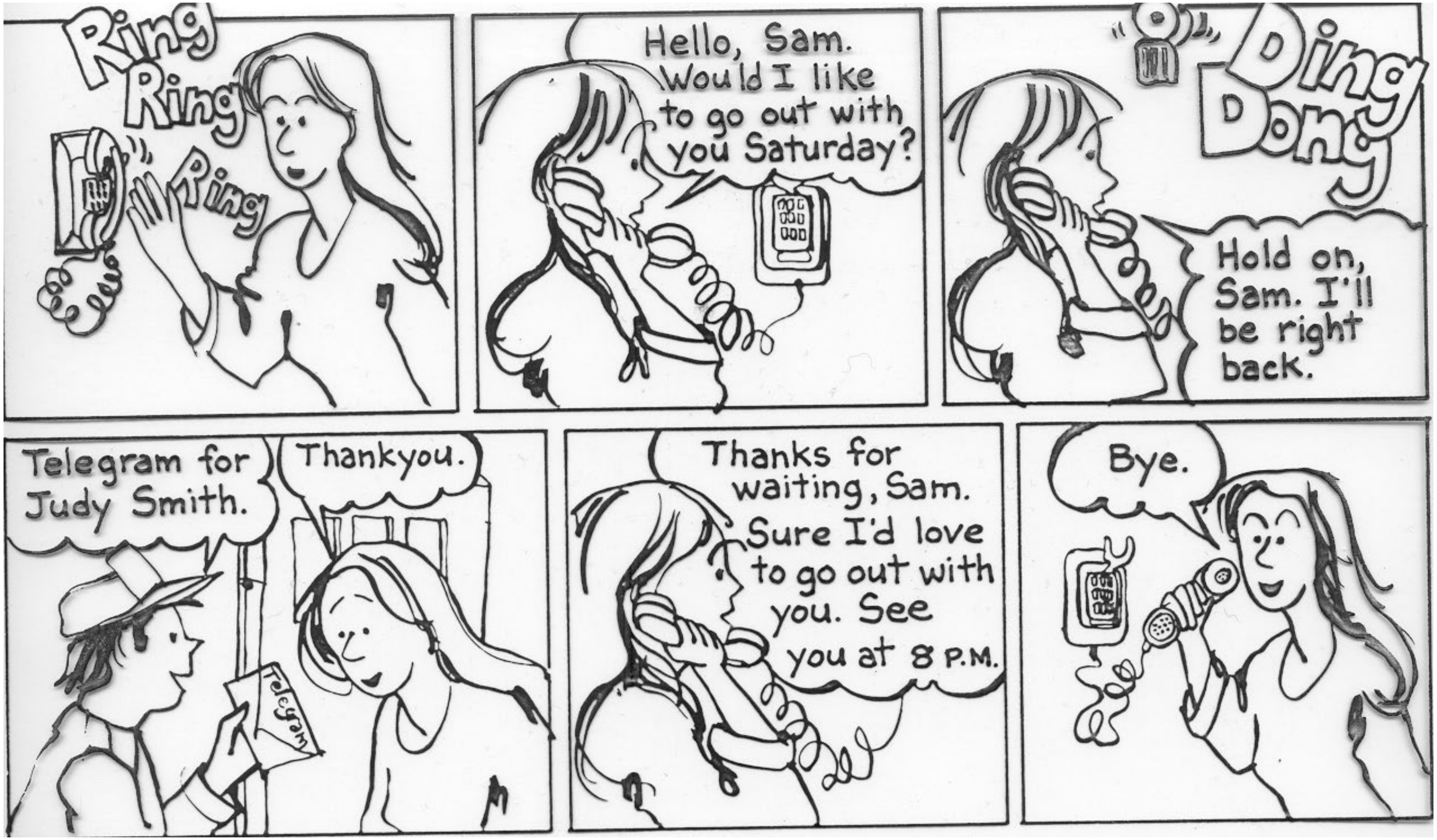
The new interrupt B is processed only when the processing of the current interrupt A has been completed.

Nested interrupt processing

- Interrupts are classified into different priority classes according to their type.
- Interrupts of higher priority may interrupt the processing of lower priority interrupts.



Nested Interrupts


Ring Ring Ring
Hello, Sam. Would I like to go out with you Saturday?
Ding Dong
Hold on, Sam. I'll be right back.
Telegram for Judy Smith.
Thankyou.
Telegram
Thanks for waiting, Sam. Sure I'd love to go out with you. See you at 8 P.M.
Bye.

Actions during interrupt processing

The first part corresponds to a regular subroutine call:

1. save return address (next instruction, PC+1) to stack
2. load program counter (PC) with entry address of interrupt handling routine (from interrupt vector table that contains the addresses of all interrupt handlers)

Under control of interrupt handler:

3. save all register contents to stack
4. perform necessary actions according to type of interrupt
5. load register contents from stack
6. return to interrupted program (by loading the return address into program counter)

8.2 Tasks of I/O

- We deal with that part of the OS that is responsible for the operation of I/O-devices, e.g.
  - Keyboard, monitor, mouse
  - Hard disks
  - Scanner, Printer
  - Measuring probes, A/D-transformer
  - Network
  - …

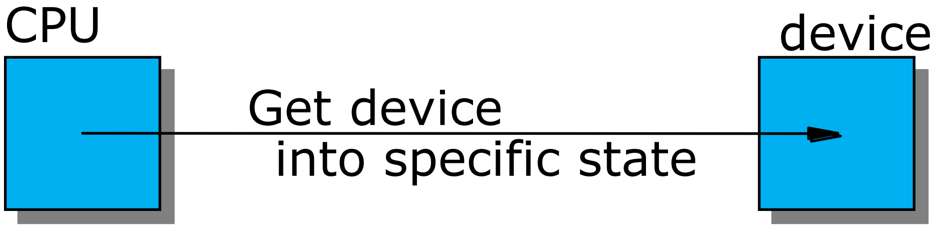
- To operate an device
  - Control positioning of movable parts, set device parameters, read status
  - Transport copy data from central unit (processor, memory) to device (or vice versa)

Diversity of devices

Device	Purpose	Partner	Data Rate (MB/s)
Keyboard	input	human	0.00001
Mouse	input	human	0.00004
Laser printer	output	human	0.3
Voice output	output	human	0.6
Network-LAN	in-/output	machine	10-10000
Mass storage	storage	machine	5-600
Graphic display	output	human	100-16000

Data rates span several orders of magnitude!

Control



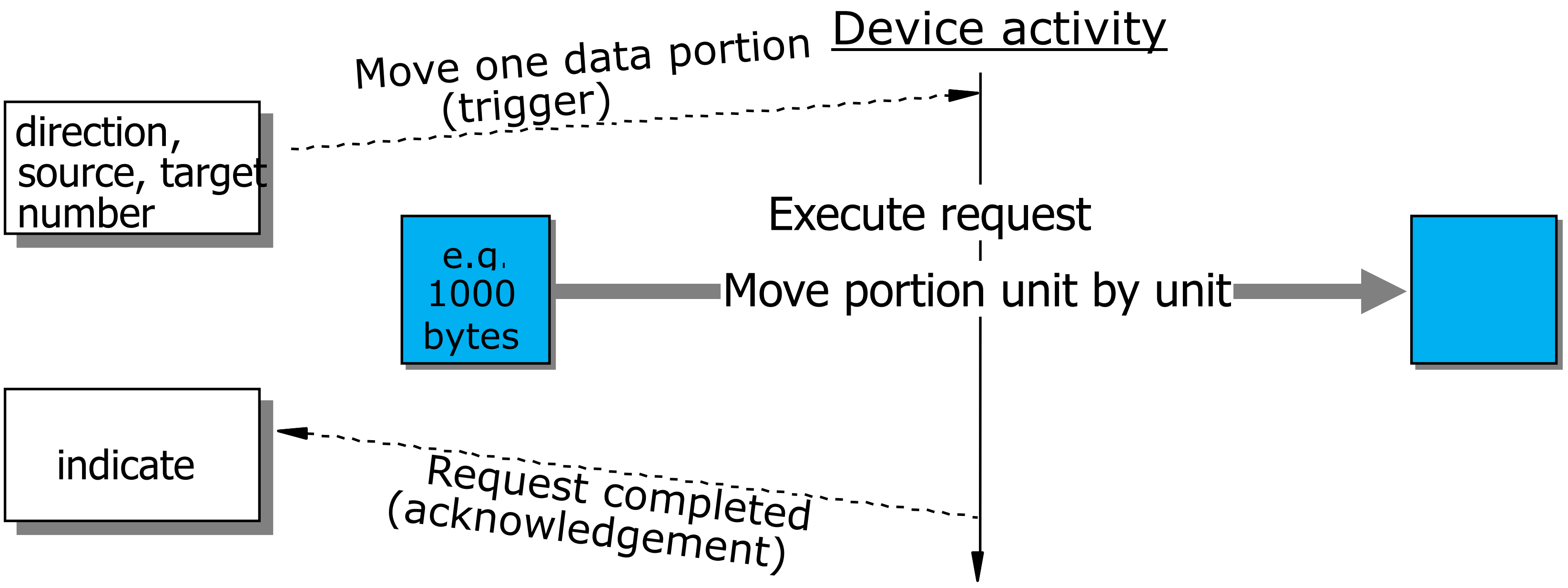
- **Examples**
  - set baud rate
  - position read/write head
  - perform page feed
  - rewind tape
  - position tape to EOT label
  - extract CD-sledge
  - ....

Portioning

- Data transport usually takes place in smaller portions

- Examples
  - Bit
    single wire
  - Byte (character)
    byte serial interface
  - Word
    word parallel interface
  - Record (several bytes)
    devices with special geometry (line printer, page printer)
  - Block (typical: 512 Byte - 8Kbyte)
    between storage devices

Handling a transport request



Device activity

direction, source, target number

Move one data portion (trigger)

Execute request

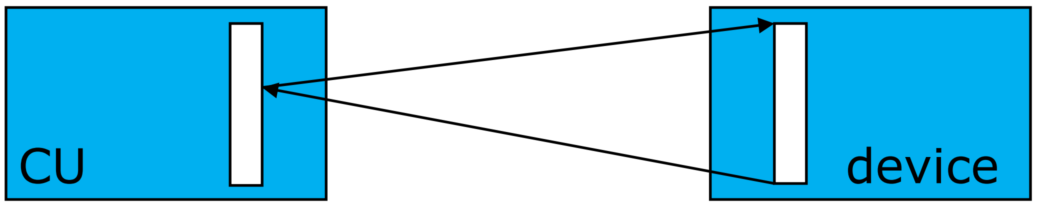
e.g. 1000 bytes

Move portion unit by unit

indicate

Request completed (acknowledgement)

The relation between the control unit (CU) and the device is obviously a **service** relation.

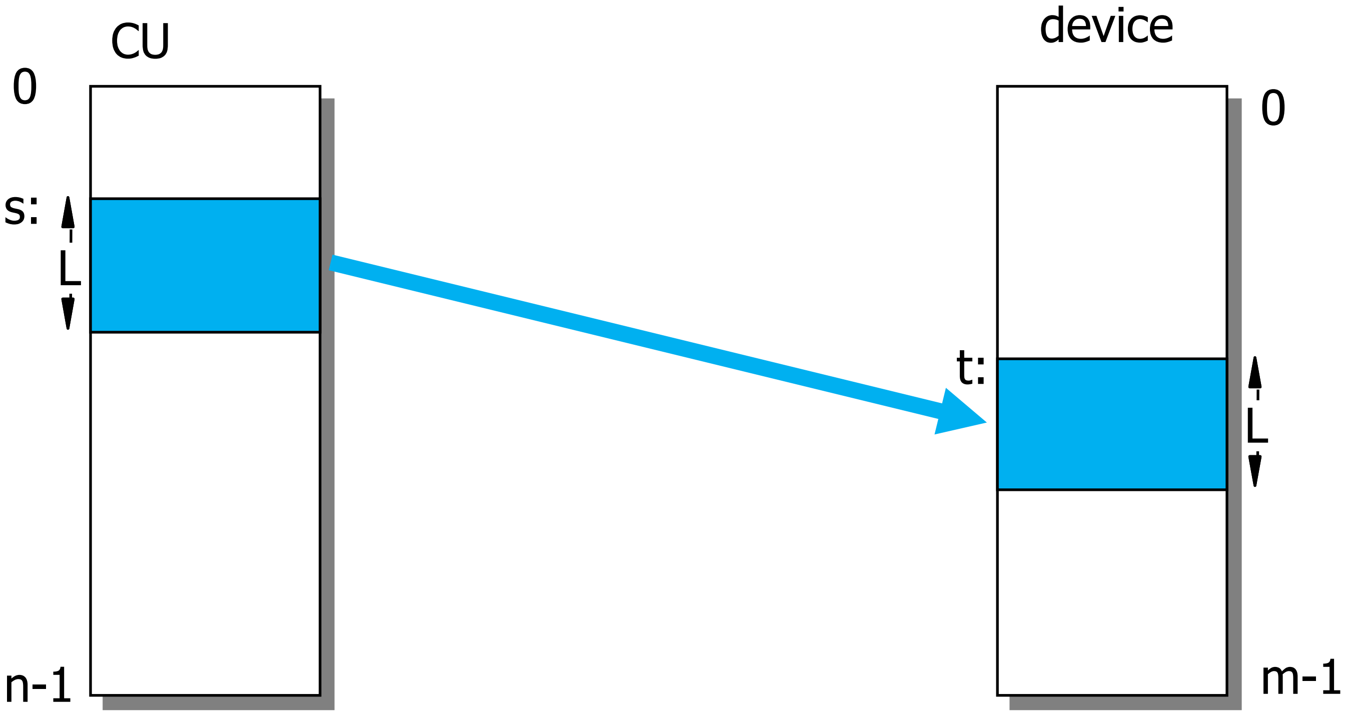


CU

device

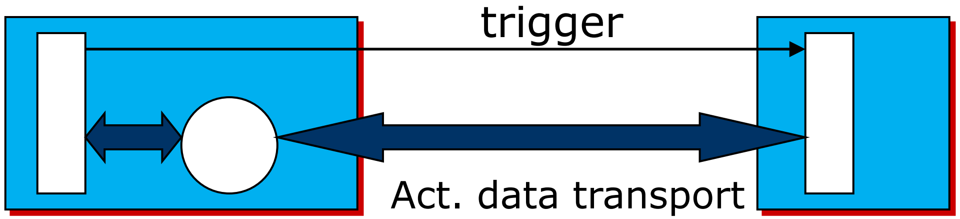
Transport request: Parameter

- Direction (read or write)?
- Where are the data (source s)?
- Where to move the data (target t)?
- How much data (length L)?



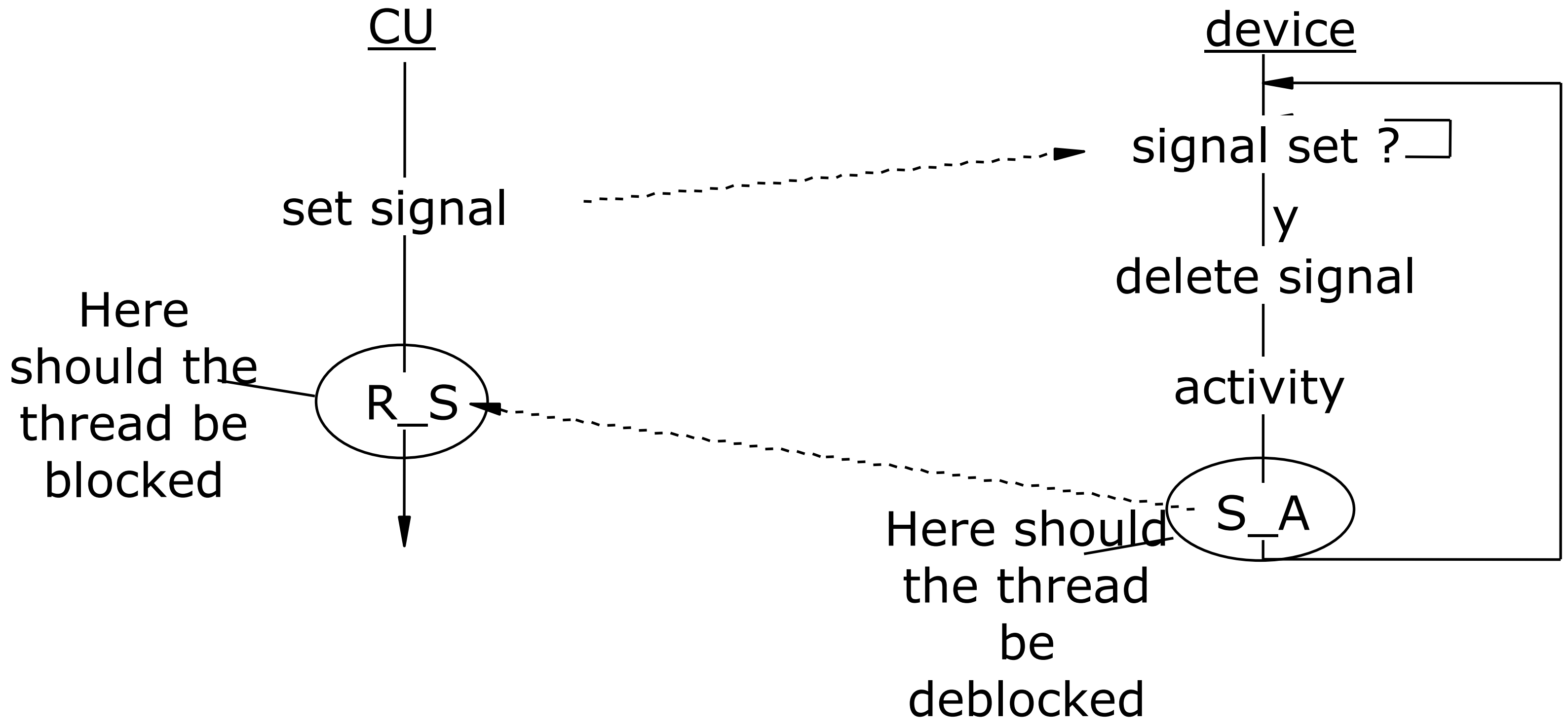
Data transport request

- We distinguish between
  - the transport request (trigger)
  - the real data transport
- Depending on the type of device more or less bytes are transmitted.
  - If it is only a few bytes, they may be included in the request itself:
    - „output character X ".
    - Transport request and data transport are the same.
  - If it is many bytes, the request is of the form:
    - „output those bytes that can be found in memory from address d_start to d_end."
  - In this case, the transport request is separated from the actual data transport.



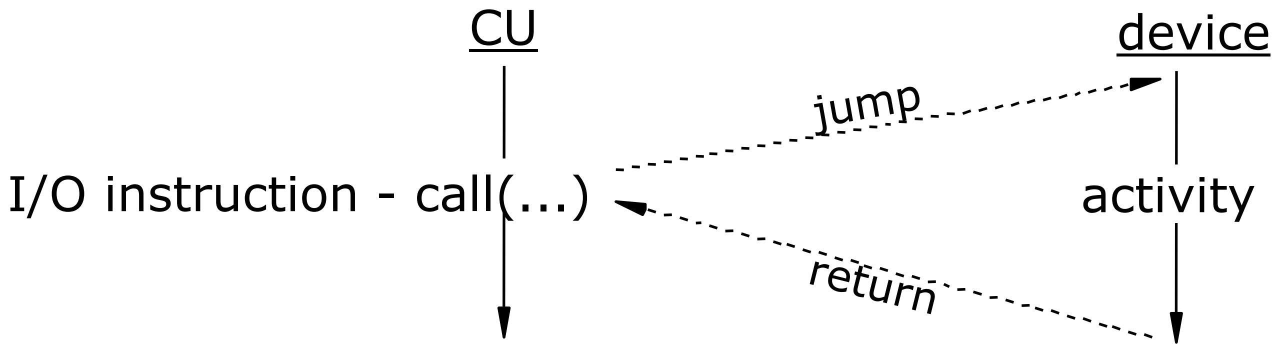
Integration of device activity into SW service structure

- Problem: How can a device send a message to a thread in order to deblock it?

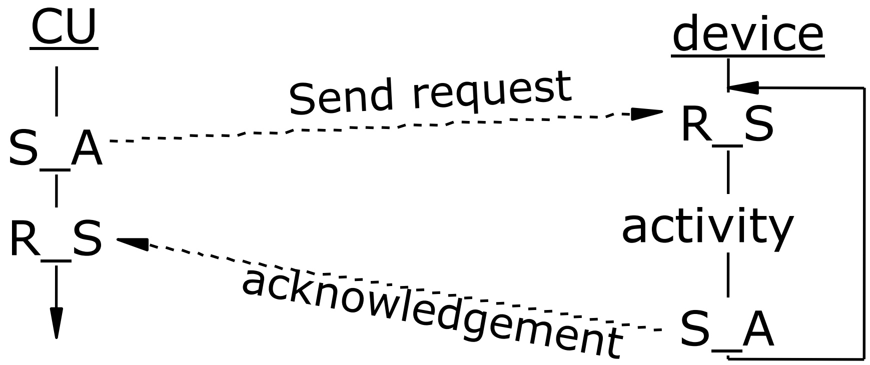

CU
set signal
Here should the thread be blocked
R_S
device
signal set ?
y
delete signal
activity
S_A
Here should the thread be deblocked

Modelling device activity

- as procedure (short activities only)



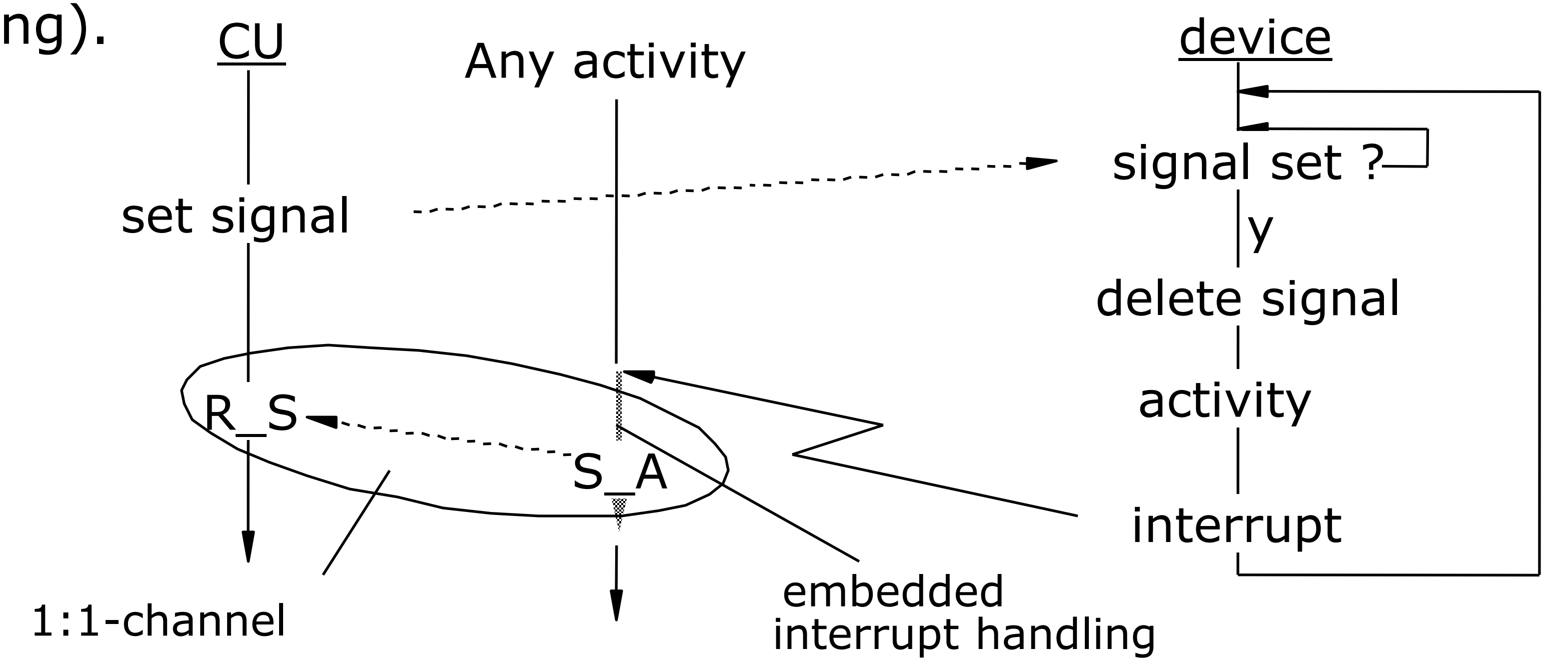
- as thread (for longer activities)



- The device can be regarded as a processor that executes exactly one thread. No switching. Active waiting for requests.

Integration of device activity into thread interaction

- Solution:
  - Device sends interrupt upon completion.
  - Processor, busy with any activity, gets interrupted and calls the respective interrupt processing routine (IPR).
  - IPR generates respective message and sends it to the requesting thread (to the channel, at which the thread is waiting).



Response

Each request processing must be checked. Many things can happen. The device provides information. In case of errors we need dedicated error processing.

Examples:

• Wrong transport parameter	memory address
	track number
	head number
	block number
• Wrong operational states	device unknown
	no voltage
	no storage media
	mechanical jam
	no formatting
• Transmission error	parity error
	synchronization error
• Media error	destroyed magnetic surface
	head crash

Technical integration

Control and transport parameter as well as indications and notifications need to flow across device boundaries: There are basically two possibilities:

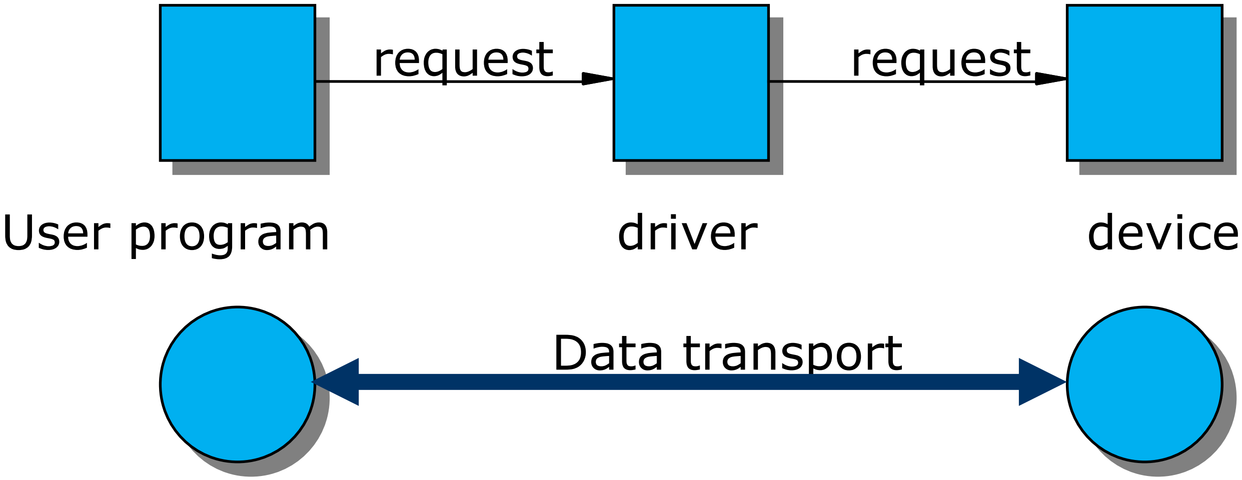
- Deposit in memory
  - Dedicated memory addresses are used as registers for device communication (*memory-mapped I/O*). They can be read and written by the device.
- Deposit in device
  - The device disposes of registers that can be read and written by the processor using special I/O instructions.

- Independent of the realization we can model these I/O registers e.g. in the following way:

```
 struct IO_register {
           PARAMETER_OF_REQUEST  IOR;
           START_SIGNAL          IOS;
           ERROR_CODE            IOE;
           FINISHED_INDICATION   IOF;
     };
```

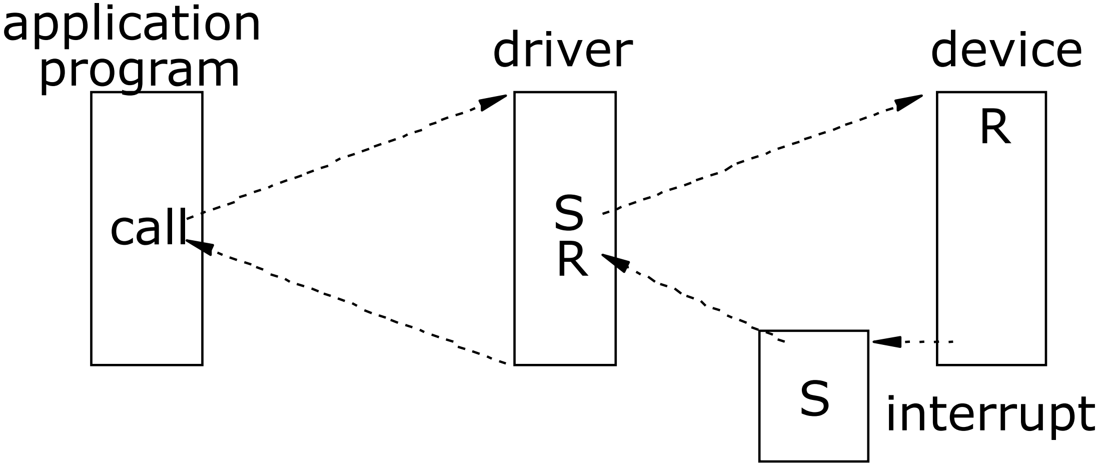
8.4 Driver

- To relieve the programmer of tedious details, all device specific activities should be confined to one single component.
- This component is called **driver**.

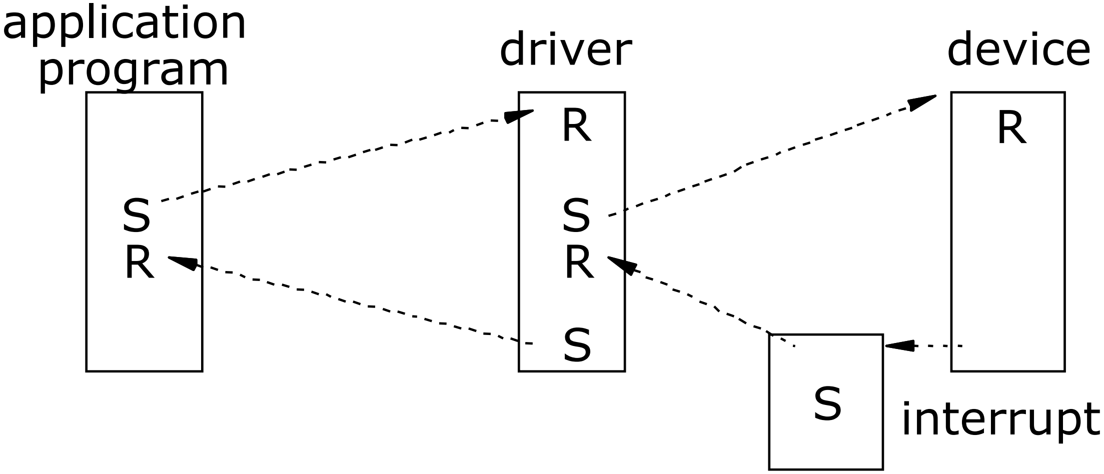


Realization of a driver

a) as procedure

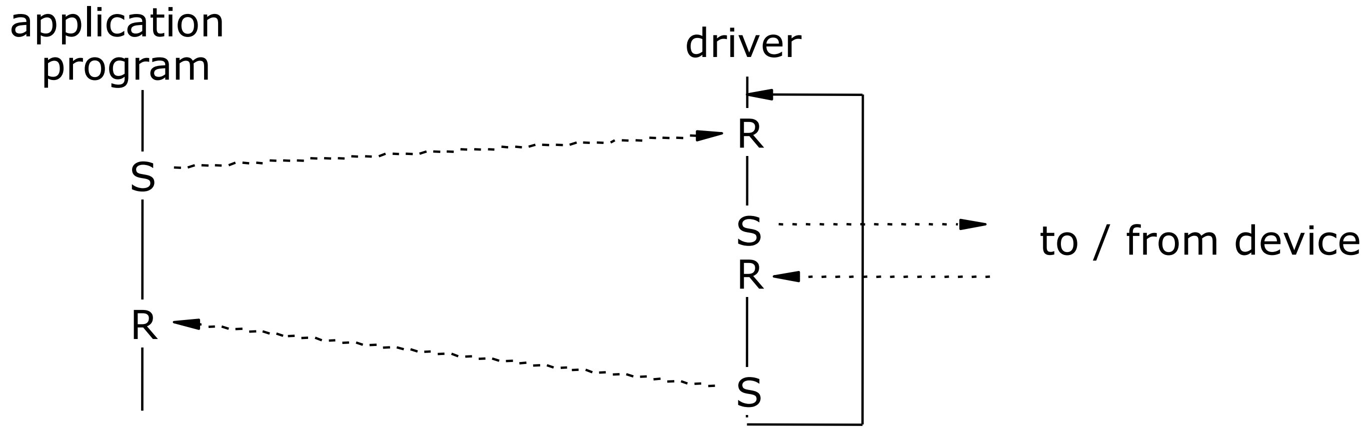


b) as thread

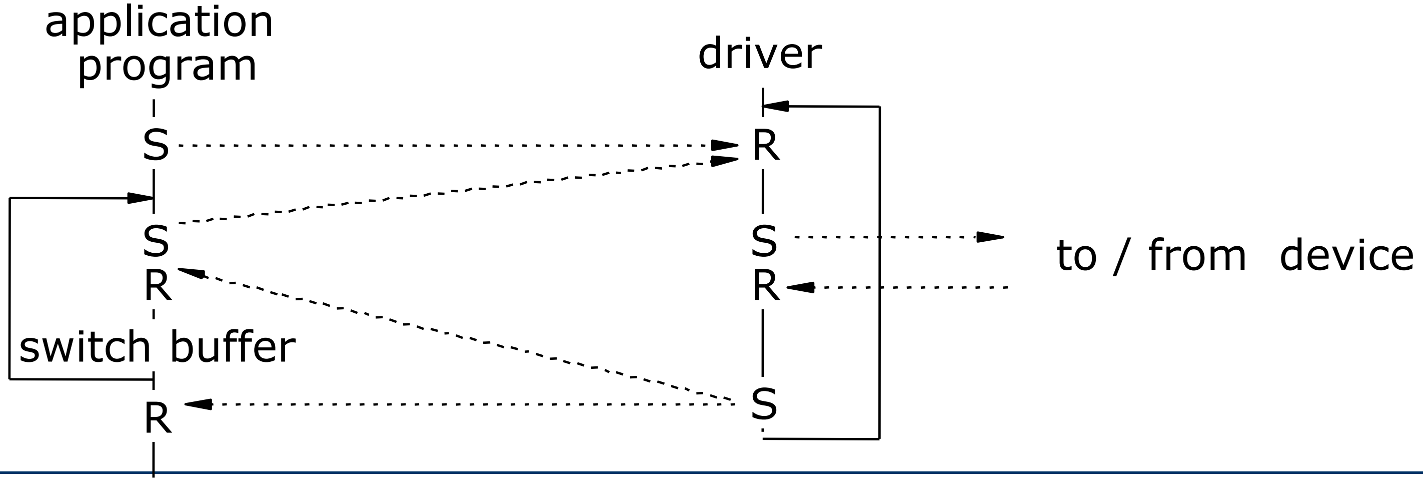


Interaction between driver and user thread

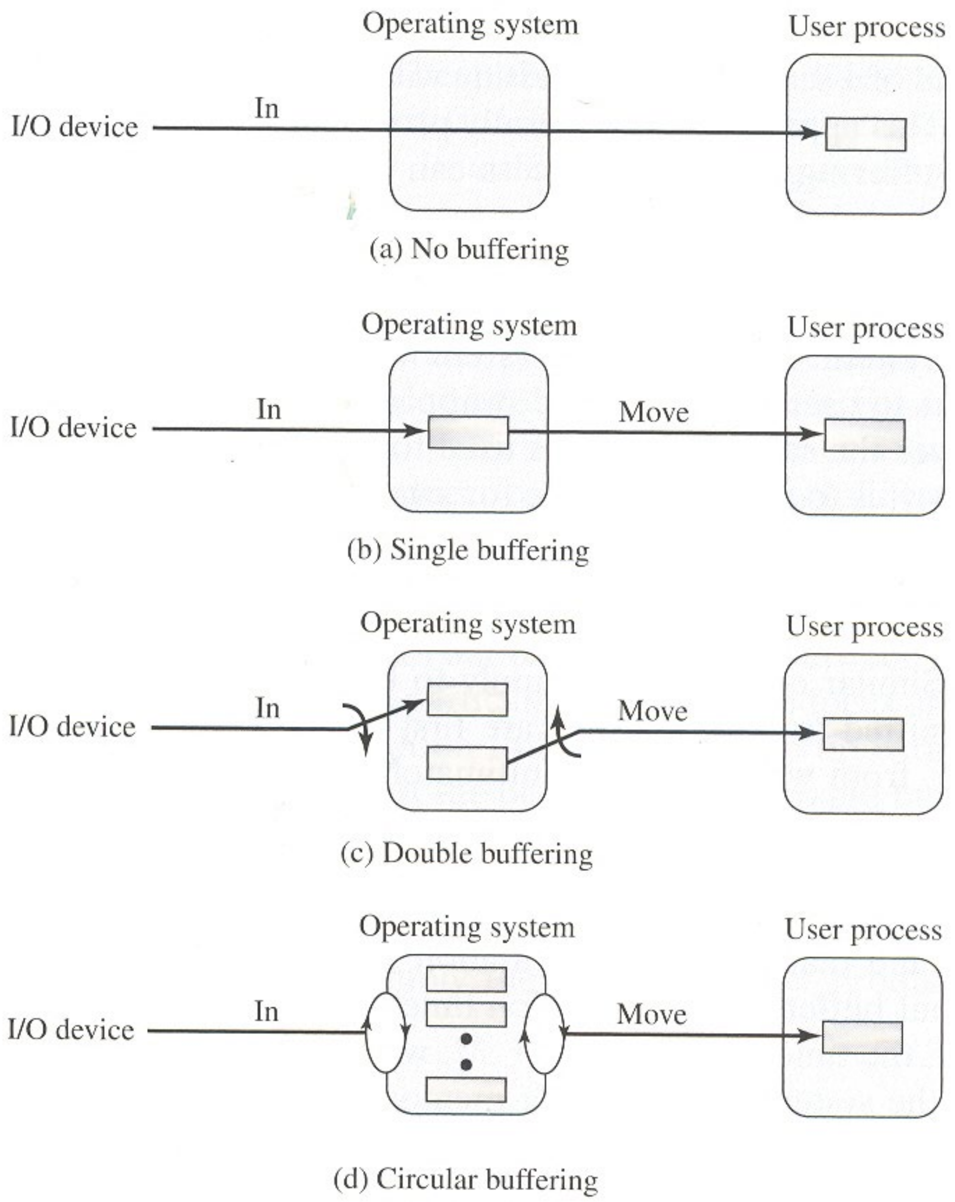
a) Parallelism between user thread and driver



b) Buffering

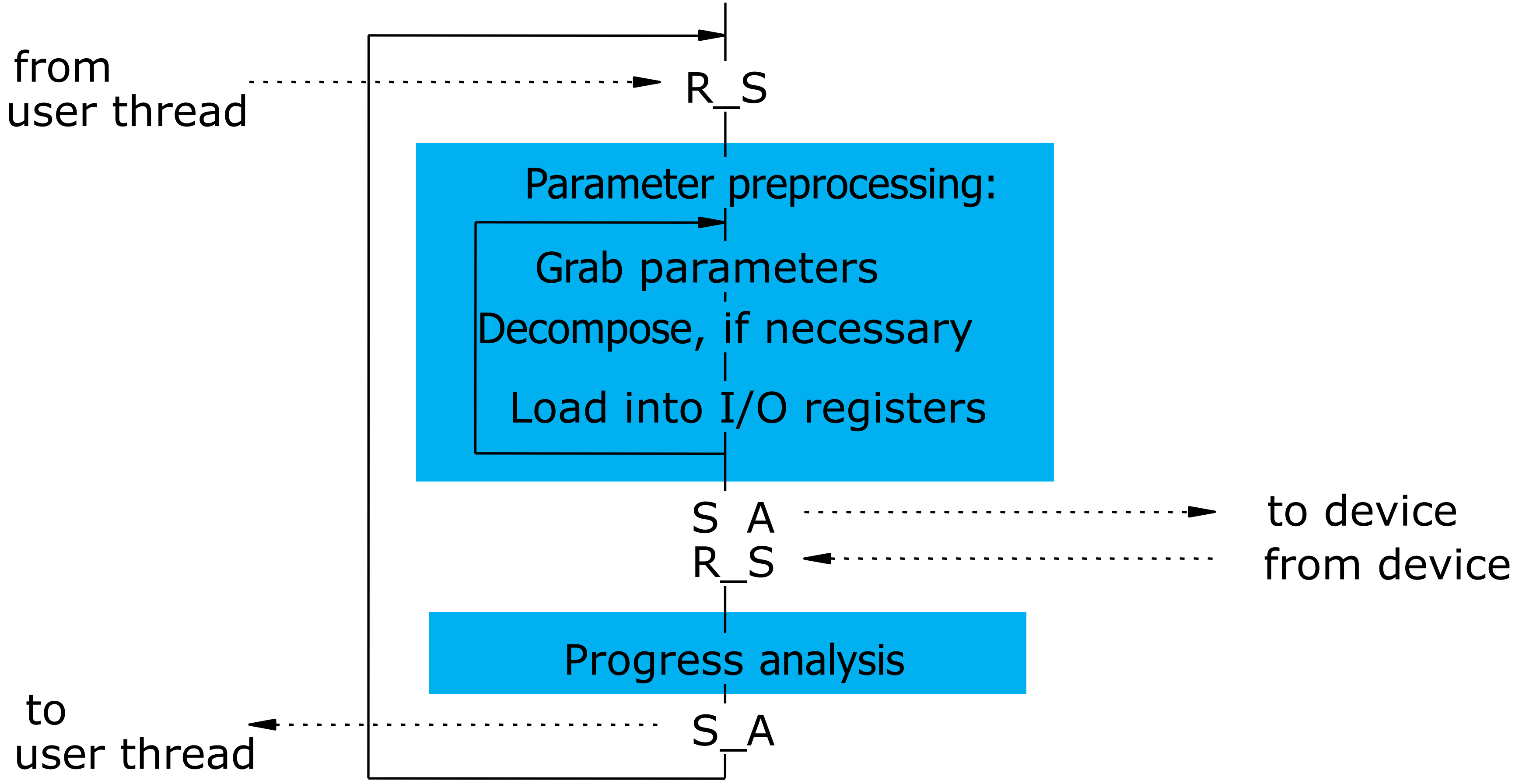


Buffering



Source : Stallings, chap. 11

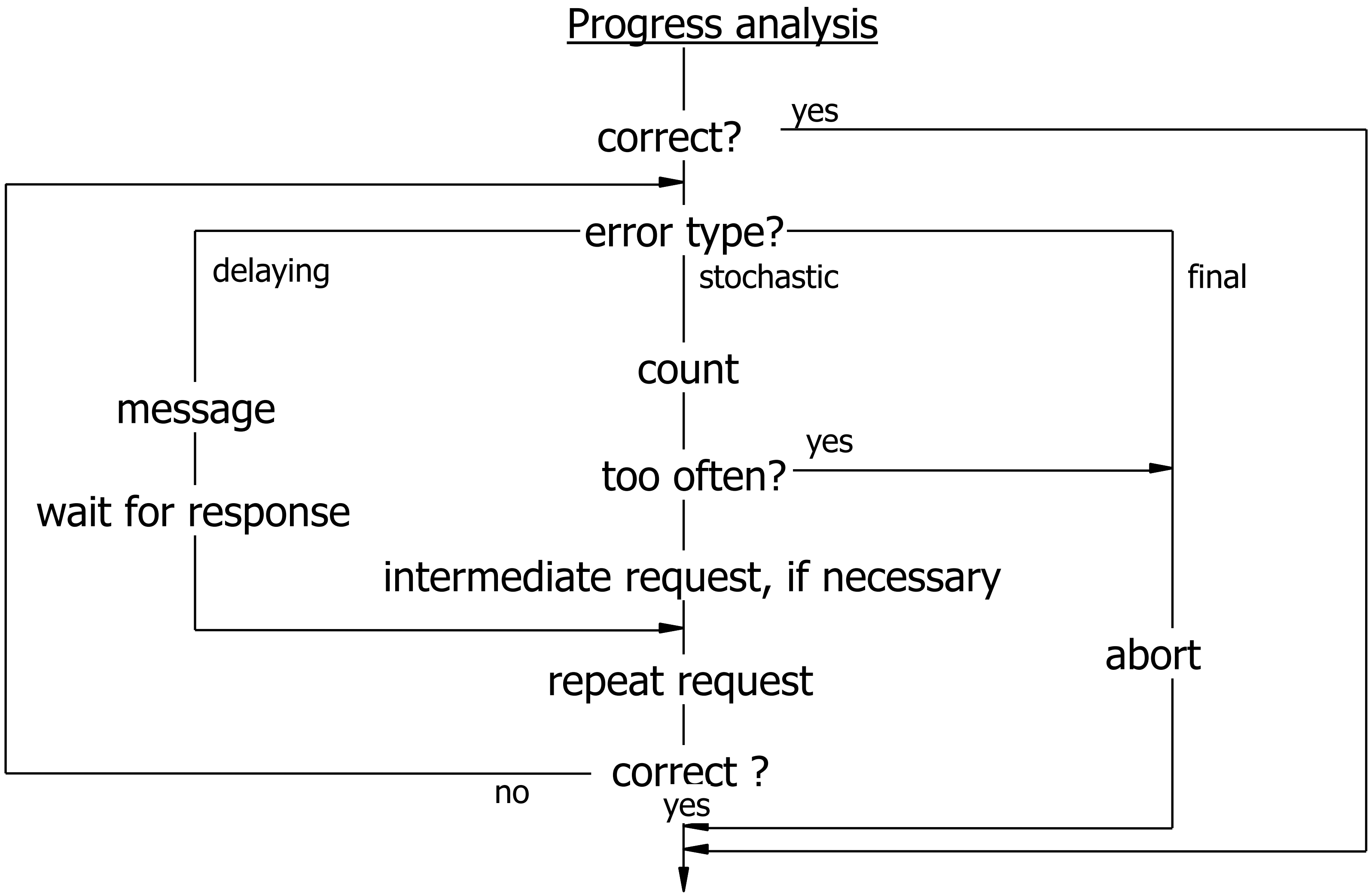
Coarse structure of a driver thread



Error handling

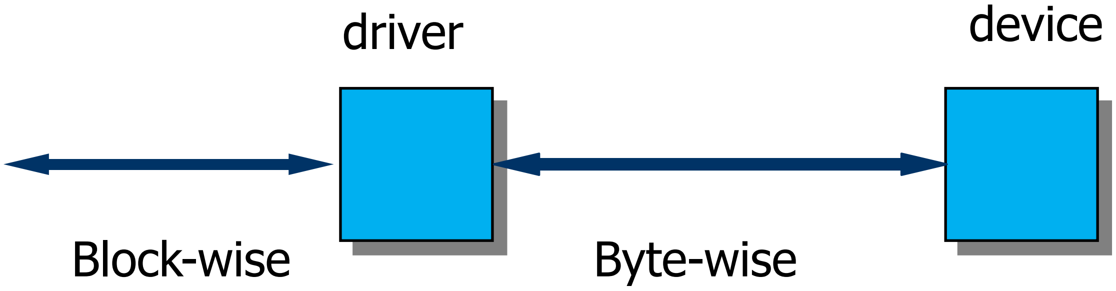
- The progress analysis mainly checks, if there were errors. If yes, action is taken, if possible.
- Regarding error handling we can distinguish three types of errors:
  - Delaying:
    Can be fixed by support of user:
    Examples: *paper tray empty, no media in drive*
  - Stochastic:
    Randomly occurring failures can be cured by repetition.
    Examples*:* *parity error, time-out, collision*
  - Final:
    If the error is not fixable, the request must be aborted:
    Examples*:* *unknown device address, no voltage*

Progress analysis



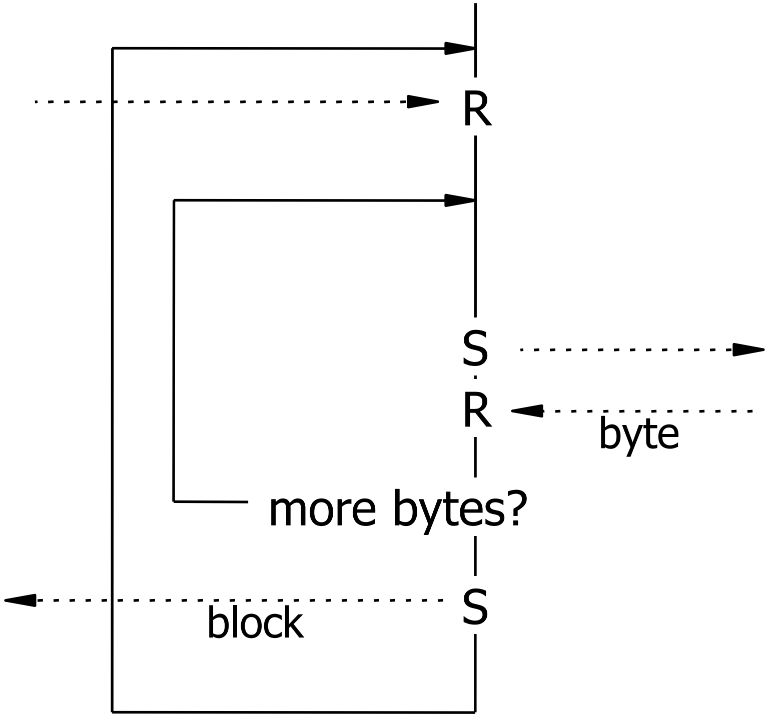
Aggregation / Disaggregation

- For devices operating byte-wise the driver often performs aggregation or disaggregation, resp., i.e. a larger set of individual characters are aggregated to a block or a block is disaggregated into individual characters.

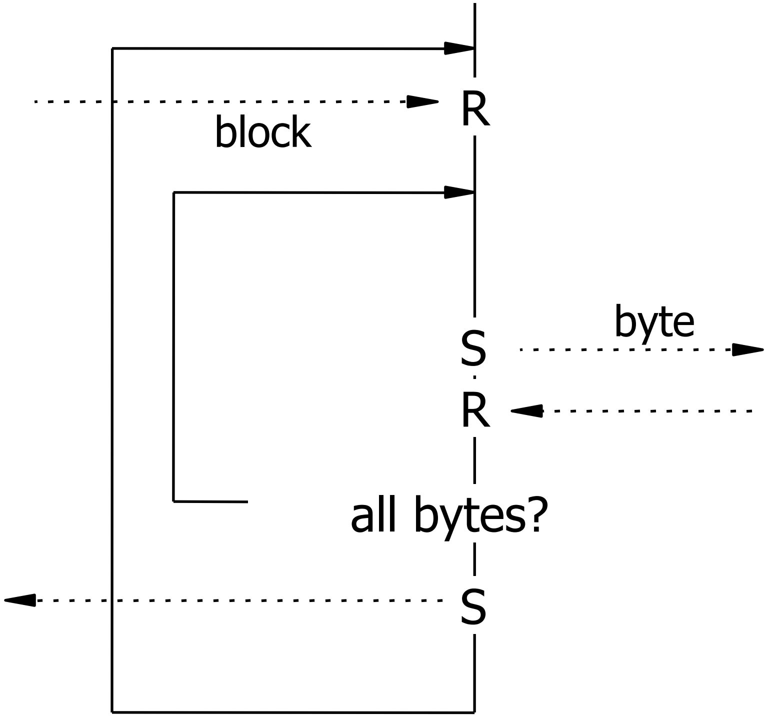


- Additionally some other tasks are performed:
  - For output, control characters are inserted (e.g. end of record, line feed, block number).
  - For input, control characters are filtered out (e.g. delete character).

Aggregation



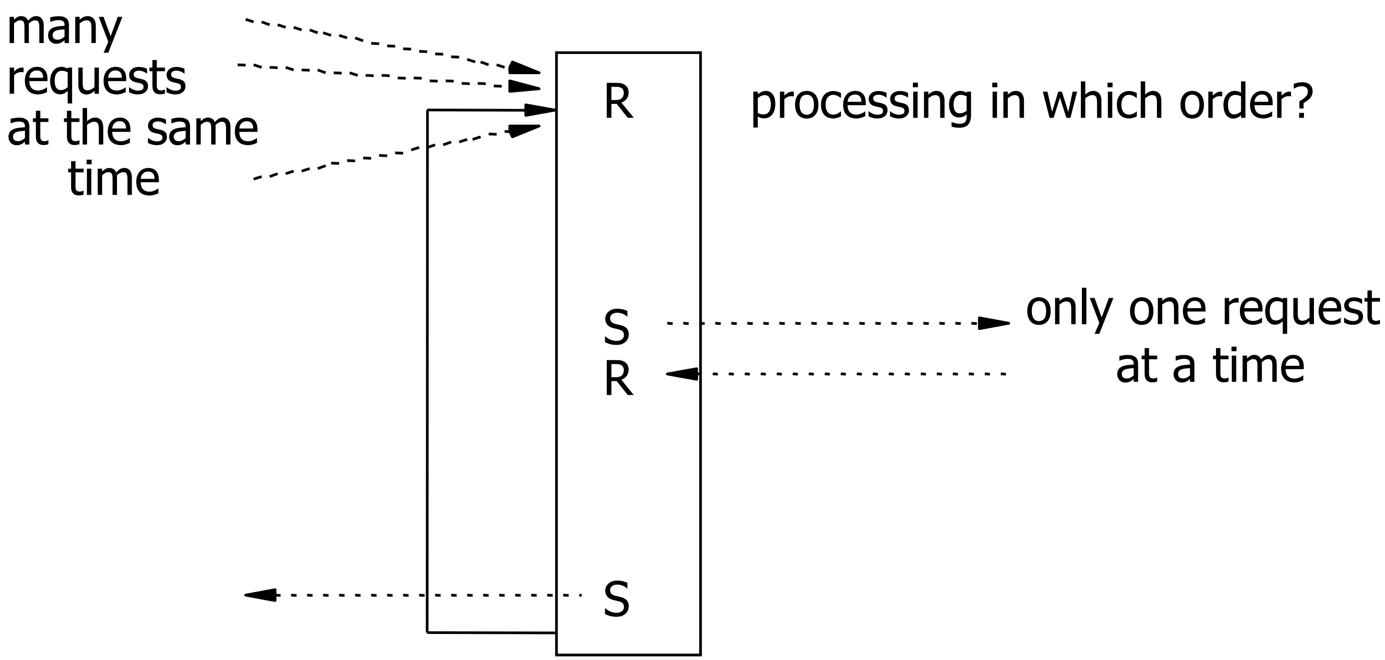
Aggregation at input



Disaggregation at output

8.5 Strategies for mass storage drivers

- A driver accepts requests from many different user threads.
- Thus, many requests may line up at its entry channel.

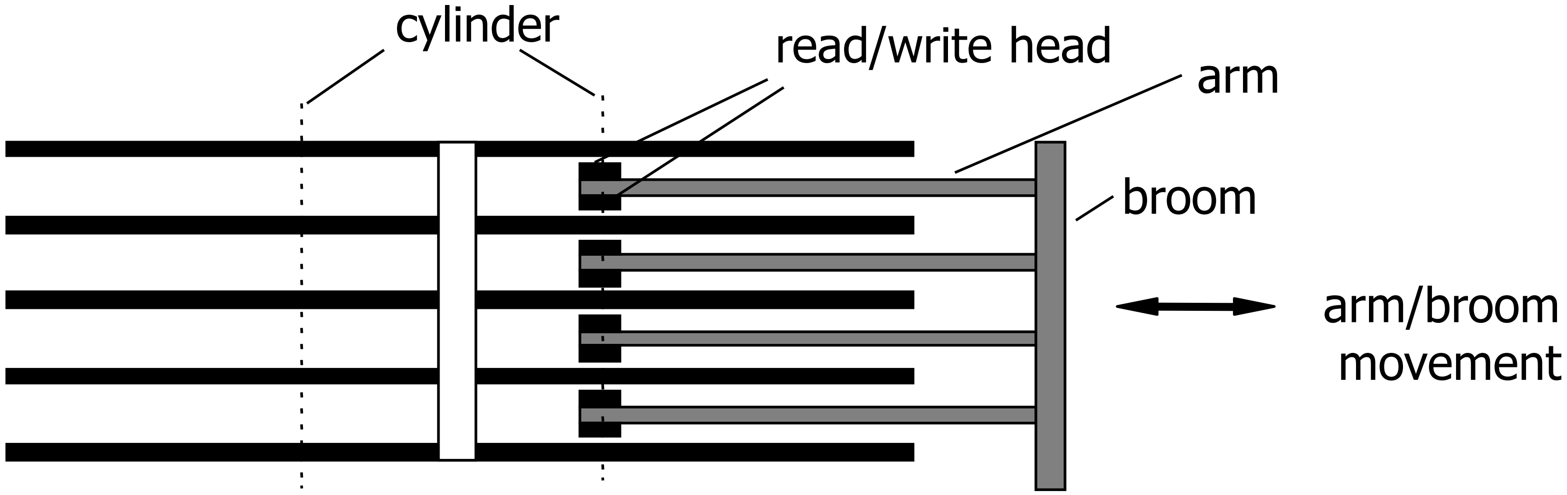

many requests at the same time
R
processing in which order?
S
R
only one request at a time
S

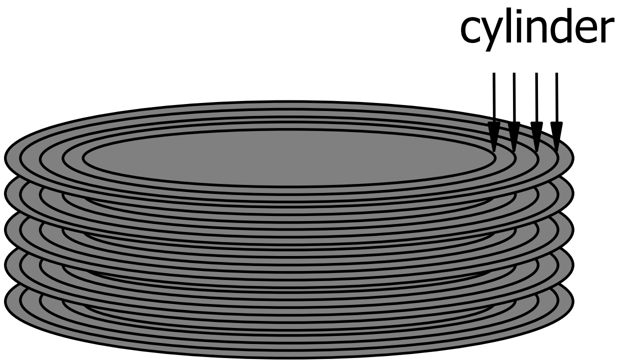
- Usually, requests are processed in the order of their arrival (FCFS, FIFO).
- **Exception: mass storage driver**

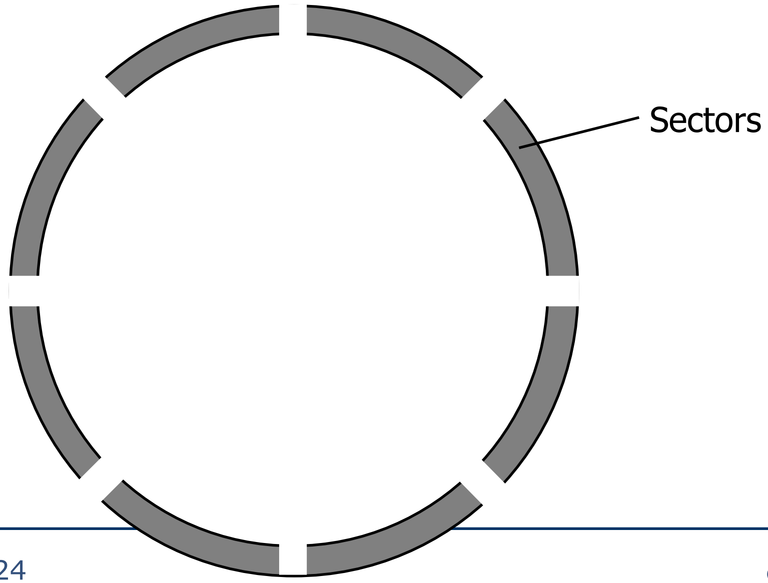
8.5.1 Hard Disk Drives (HDDs)

- A hard disk consists of one or more platters with magnetizable surfaces that rotate at high speed (ca. 3000-10000 rpm).
- For each magnetizable surface there is a **read-write head** that can be moved back and forth across the whole surface. The gadget that holds the read/write heads is called disk **arm**.
- If the disk device consists of more than one platter, the different arms are attached to a **broom**.
- Each surface consists of concentric **tracks** (1000-20000), on which the information is recorded.
- Each track in turn is composed of many **sector** (50-800).
- Each sector can store a specific amount of data (normally 0.5 or 4 kByte)
- The entirety of all tracks that can be read/written with the same arm position, is called **cylinder**. (In case of only one surface, cylinder and track are the same.)

Geometry of a hard disk







Example: Hitachi Travelstar 7K500

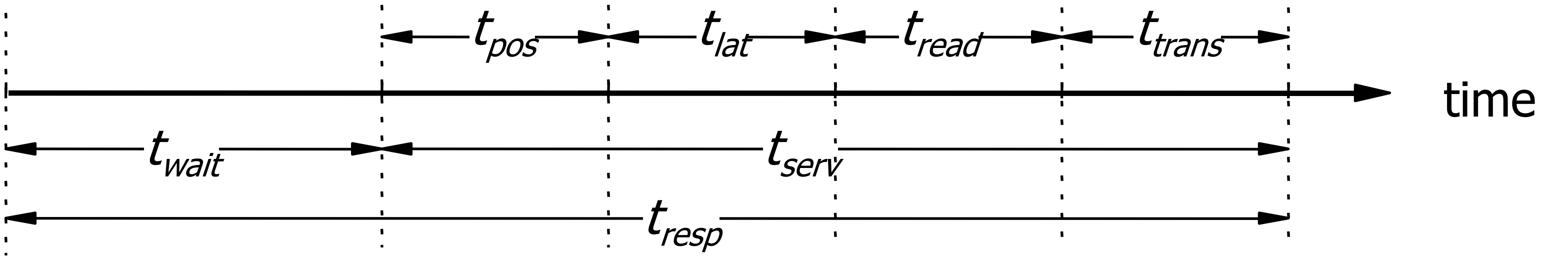
Capacity (formatted)	320 GB
Bytes per Sector	512 Bytes
Positioning time (next track)	1 Milliseconds
Positioning time (average)	12 Milliseconds
Positioning time (max)	20 Milliseconds
average latency	4.2 Milliseconds
rotational speed	7,200 rpm
Transmission rate (max.)	1245 Mbit per sec
Internal buffer	16 MB
Storage density (max.)	370 Gbit/sq.in.

Parameters

- The service time t_{serv} of a disk request (*op, n, s*) to read or write from sector *s* on track *n* is additively composed of the following components:

Arm positioning time t_{pos}	time needed to move the arm from its current position to position n
Latency t_{lat}	waiting time until the target sector appears under the head (rotational waiting time)
Read/write time t_{read}	time for reading /writing the target sector
Transfer time t_{trans}	time to transmit the block from or to main memory

- In addition to this service time t_{serv} we have to calculate the waiting time t_{wait} to get the total response time t_{resp} :



Example

- Assume we have a hard disk with the following parameters:

Arm positioning time	10 ms
Rotational speed	10.000 rpm
Sector size	512 bytes
Sector number	320/track

- Read request with following parameters:
  - 2560 Sectors, i.e. 1,3 Mbytes

- Question: What is the service time?

Example

- Case 1:

  File is contiguously stored, i.e. it allocates all sectors on 8 adjacent tracks (8 x 320 = 2560 sectors).

Arm positioning time	10 ms	
Latency	3 ms	(half rotation)
Reading 320 sectors	6 ms	(= 1/ (10.000 / 60) sec)
Total	19 ms	for first track

The remaining tracks can be read without additional delay, i.e. the average positioning time is neglectable (zero).

Thus, for each remaining track we get 6+3=9 ms.

In total we calculate a service time* of 19 + 7x9 = **82 ms**

* without transfer time to copy data into main memory

Example

- Case 2:
  File is stored randomly, i.e. it occupies sectors on any tracks.

Arm positioning time	10 ms
Latency	3 ms
Reading 1 sector	0.01875 ms (6 ms / 320)
Total	13.01875 ms for each sector

  Since we have to read 2560 sectors, we get a total service time of

  2560 x 13.01875 = 33,328 ms = **33.328 Seconds**

Lesson learned: Files should occupy contiguous sectors!

Strategies for hard disks

a) First come first served (FCFS)

Processing requests in the order of their arrival

b) Shortest seek time first (SSTF)

Always select request with the shortest arm positioning time

c) Elevator (SCAN)

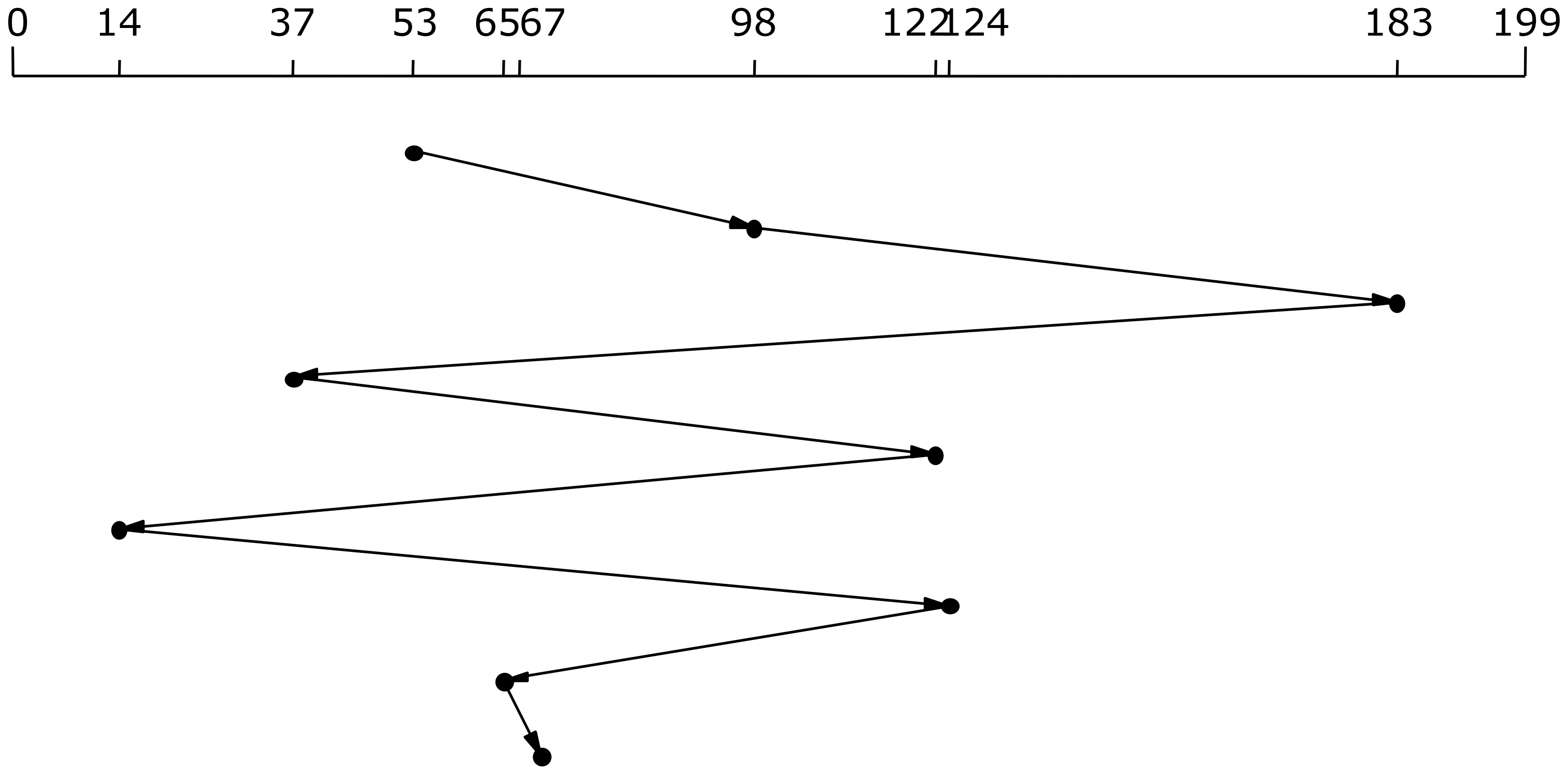
Like SSTF, but only in one direction

d) Cyclic Elevator strategy (SCAN-C)

Like SCAN, but return to track 0 when reaching highest track number

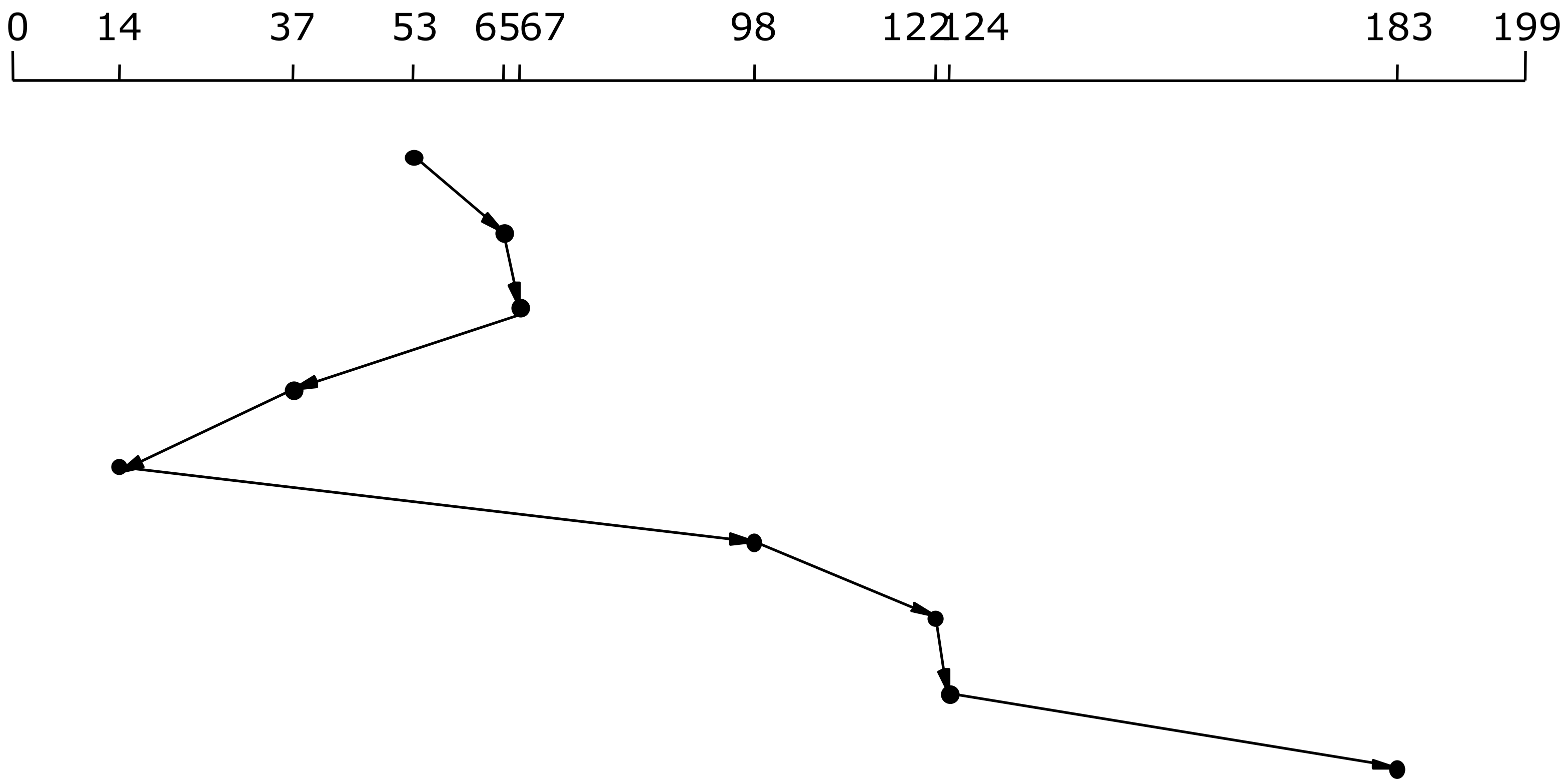
Example FCFS

- Requests in queue (track number): 98, 183, 37, 122, 14, 124
  65, 67
- Current head position: 53



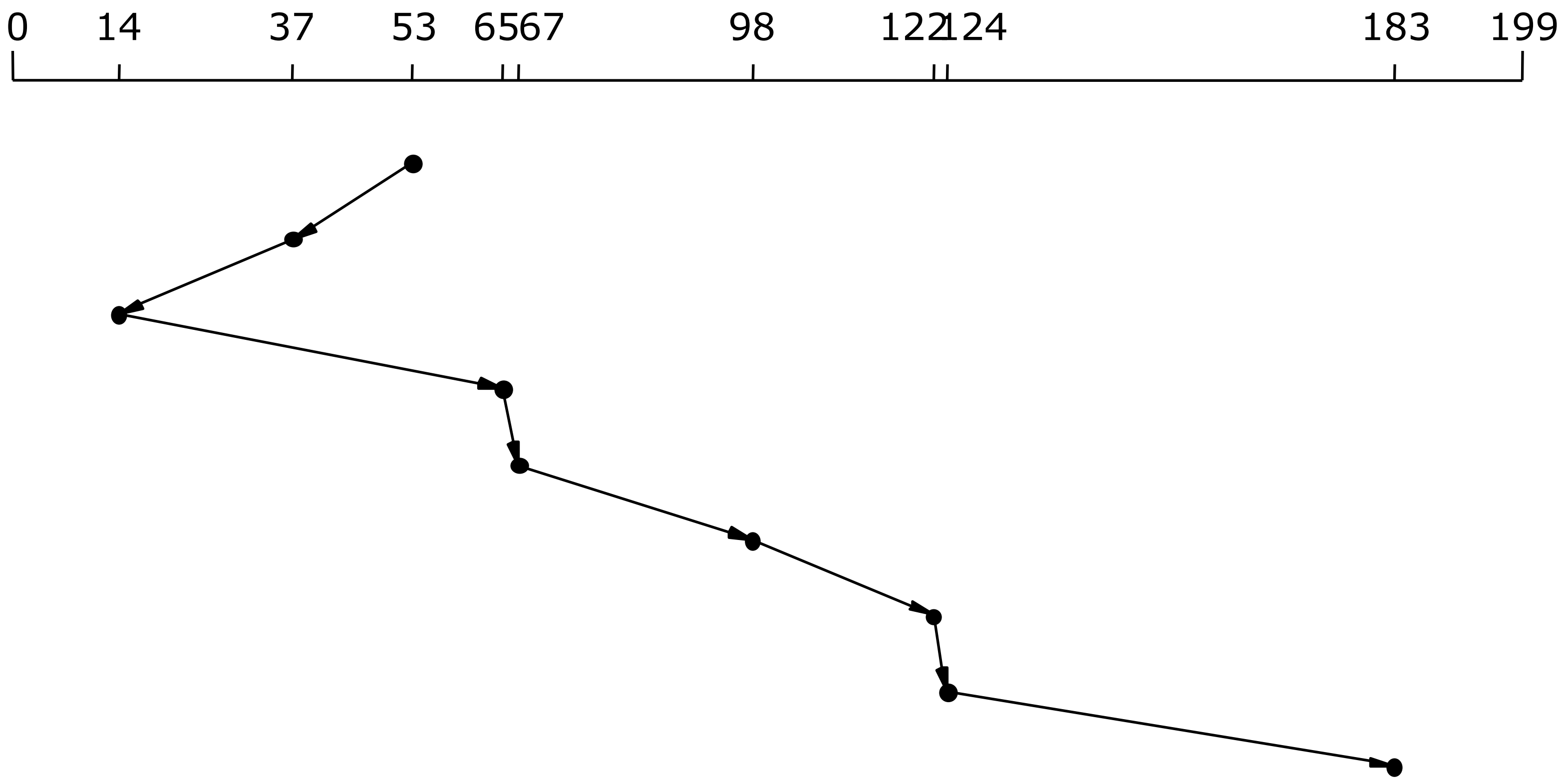
Example SSTF

- Requests in queue (track number): 98, 183, 37, 122, 14, 124
  65, 67
- Current head position: 53



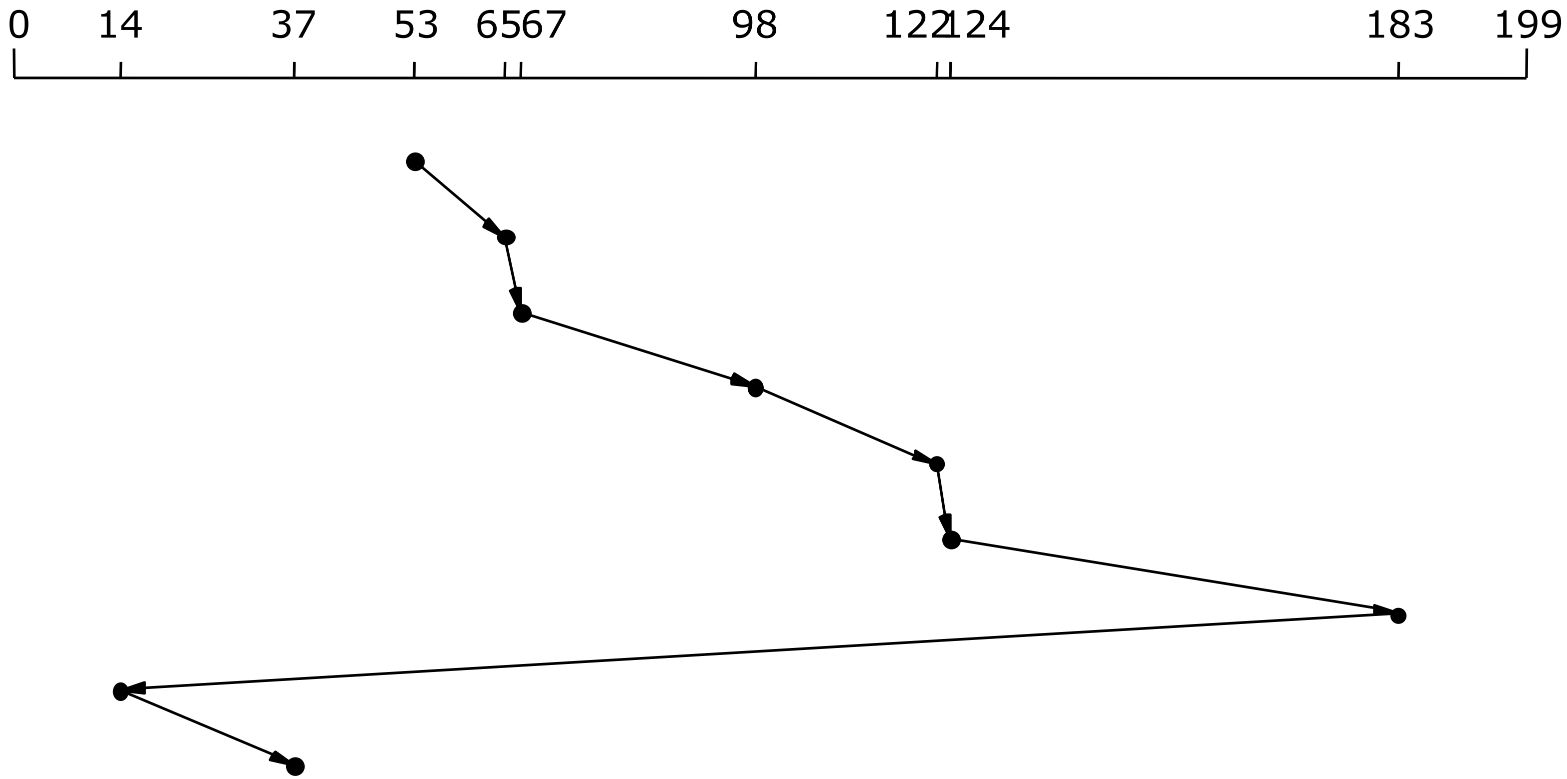
Example SCAN (Elevator)

- Requests in queue (track number): 98, 183, 37, 122, 14, 124
  65, 67
- Current head position: 53
- Current direction: down

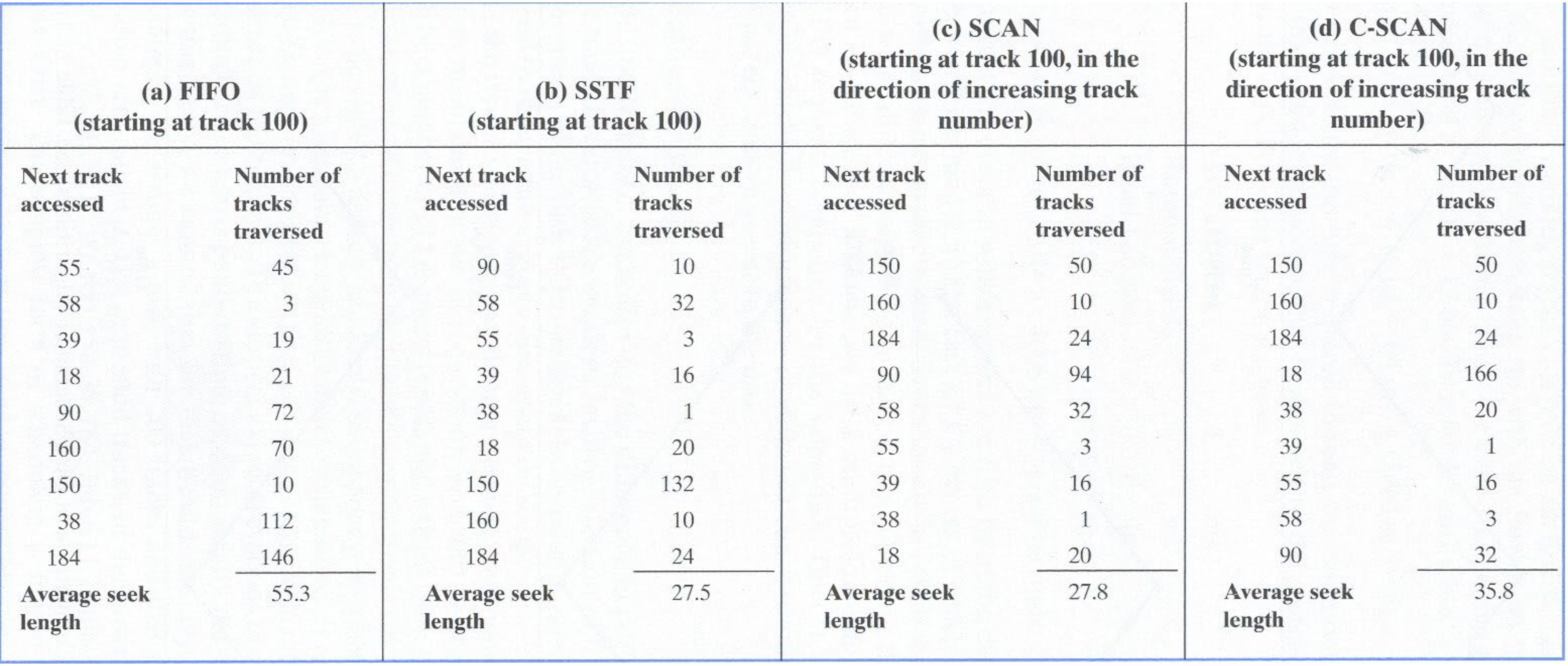


Example SCAN-C

- Requests in queue (track number): 98, 183, 37, 122, 14, 124
65, 67
- Current head position: 53



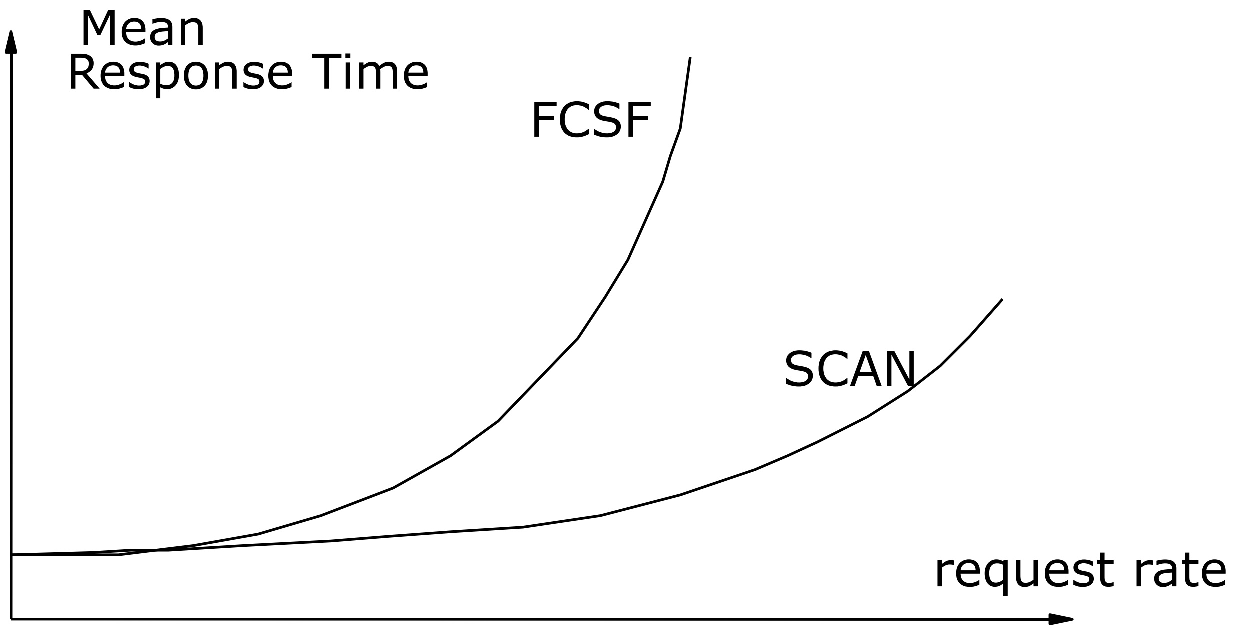
Example



(a) FIFO (starting at track 100)		(b) SSTF (starting at track 100)		(c) SCAN (starting at track 100, in the direction of increasing track number)		(d) C-SCAN (starting at track 100, in the direction of increasing track number)	
Next track accessed	Number of tracks traversed	Next track accessed	Number of tracks traversed	Next track accessed	Number of tracks traversed	Next track accessed	Number of tracks traversed
55	45	90	10	150	50	150	50
58	3	58	32	160	10	160	10
39	19	55	3	184	24	184	24
18	21	39	16	90	94	18	166
90	72	38	1	58	32	38	20
160	70	18	20	55	3	39	1
150	10	150	132	39	16	55	16
38	112	160	10	38	1	58	3
184	146	184	24	18	20	90	32
Average seek length	55.3	Average seek length	27.5	Average seek length	27.8	Average seek length	35.8

Source : Stallings, chap. 11

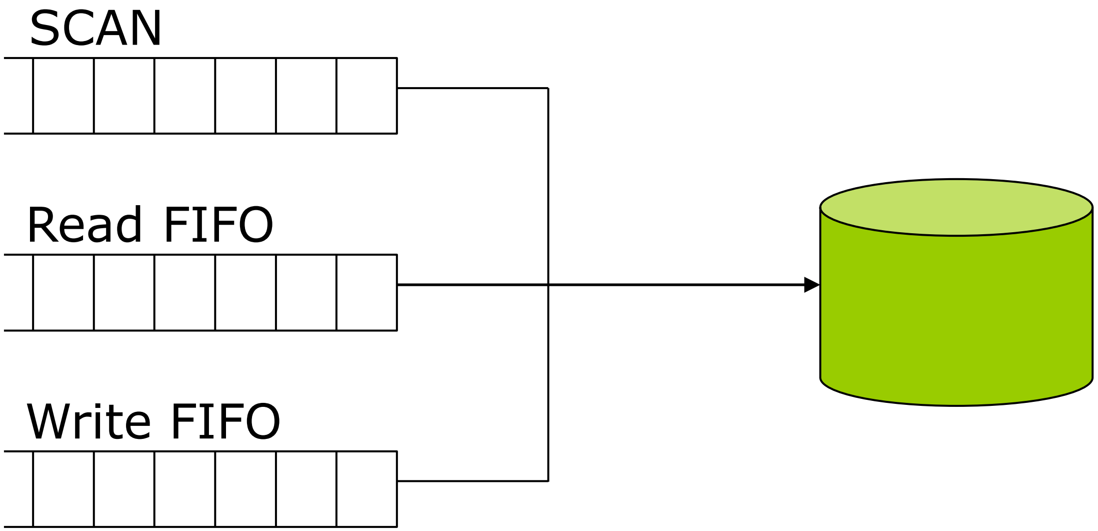
Remarks



- FCFS requires on the average (uniform distribution) moving across 1/3 of the tracks.
- SCAN, SCAN-C, SSTF are advantageous for high load since (in the limit) we have to move only one track.
- SCAN and SSTF discriminate against marginal tracks (inmost and outmost).
- SSTF is generally the best. However, it can lead to starvation of request for marginal tracks.

Linux Deadline Scheduler

- The elevator strategy (SCAN) can lead to “starvation”.
- Write accesses are usually asynchronous, read accesses synchronous. A stream of write accesses can therefore significantly delay a read access.
- Therefore, each request is furnished with a deadline and additionally (besides the SCAN-Queue) inserted into a read or write queue.
- In the normal case the SCAN queue is being processed, unless the first request of one of the FIFO queues becomes overdue (deadline expired). Then this request (and some more) of the respective FIFO queue are processed.



Realization of non-FCFS strategies

Sorting of requests according to track number can be done:

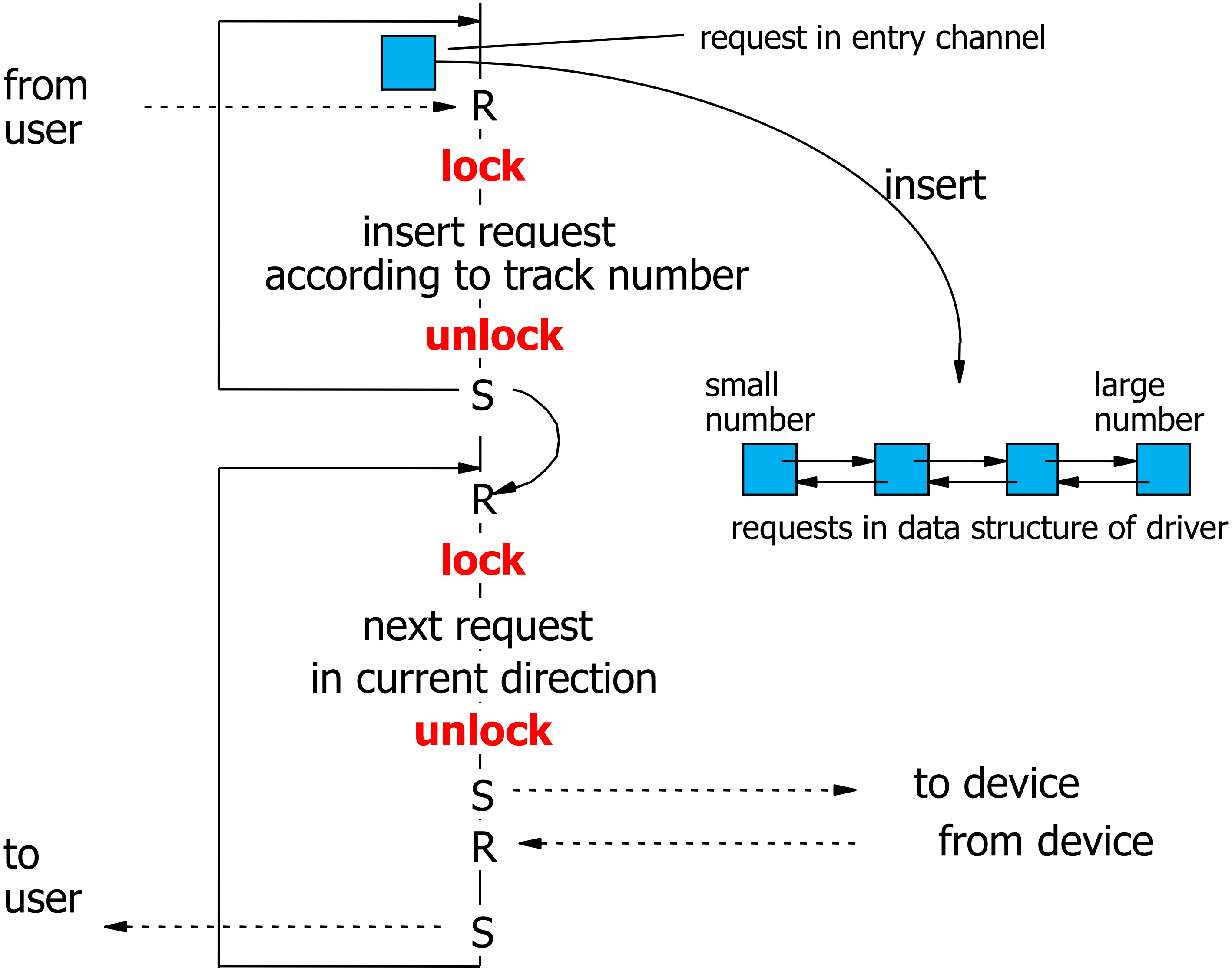
- In the communication operations at the driver‛s entry channel. Means special variant of channel (receive).
- In the driver itself, i.e. all incoming request are admitted to the driver.

Requires parallelism between

- Request acceptance
- Request processing

Pipeline!

Driver as Pipeline



from user

R

lock

insert request according to track number

unlock

S

R

lock

next request in current direction

unlock

S

R

S

to user

request in entry channel

insert

small number

large number

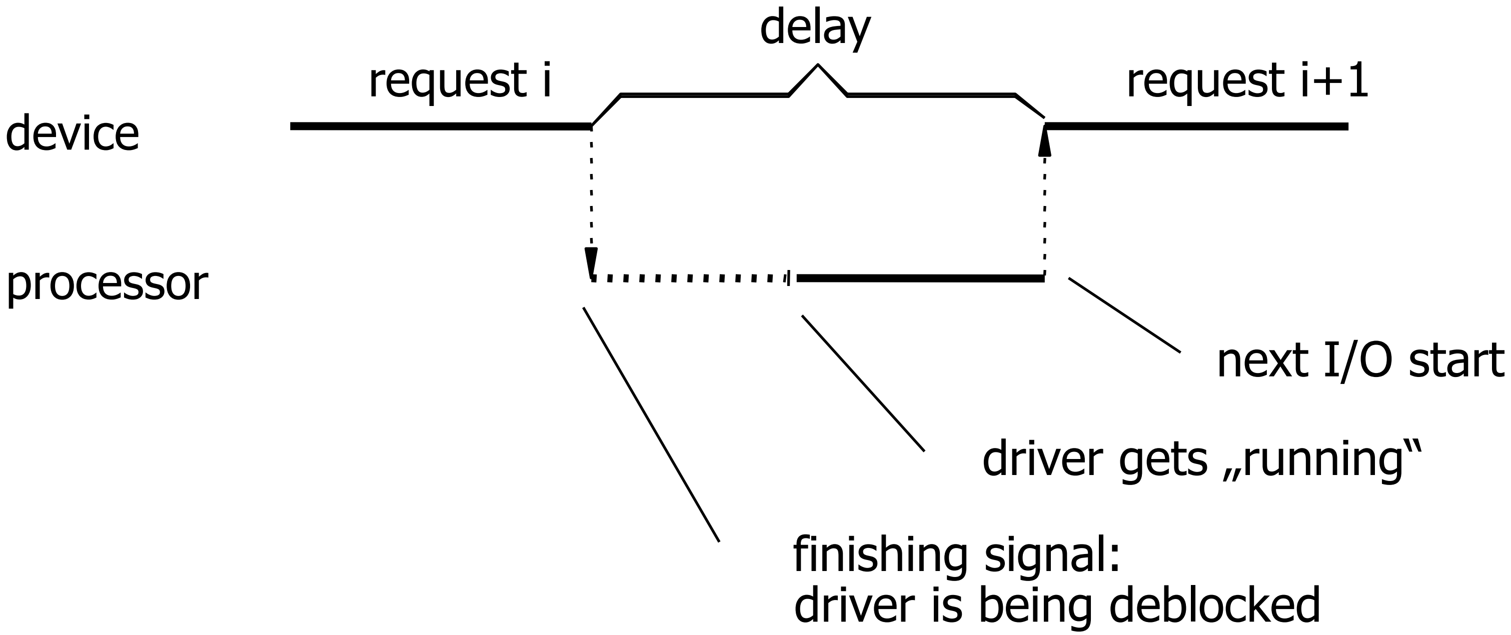
requests in data structure of driver

to device

from device

Delay time reduction

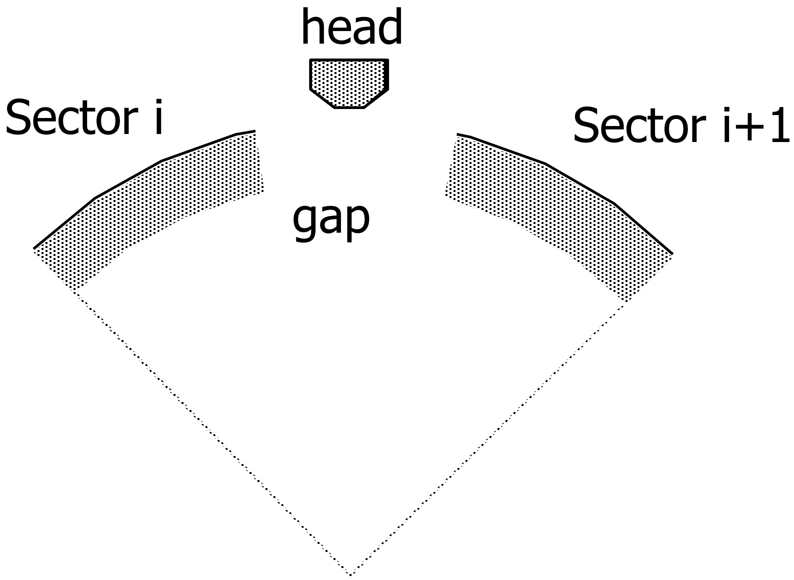
- According to the current state of discussion the driver gets blocked if it has submitted a request to the device (entering a synchronous receive).
- Deblocking takes place as part of the interrupt handling, when the request processing is finished.
- Even if the driver runs at high priority, some time elapses, until the driver can submit the next request.



Latency Hiding

- At sequential access to disk the time between two successive requests should not be longer than the time needed to move across a sector or block gap.
- Otherwise the next sector can be read only after one full rotation.

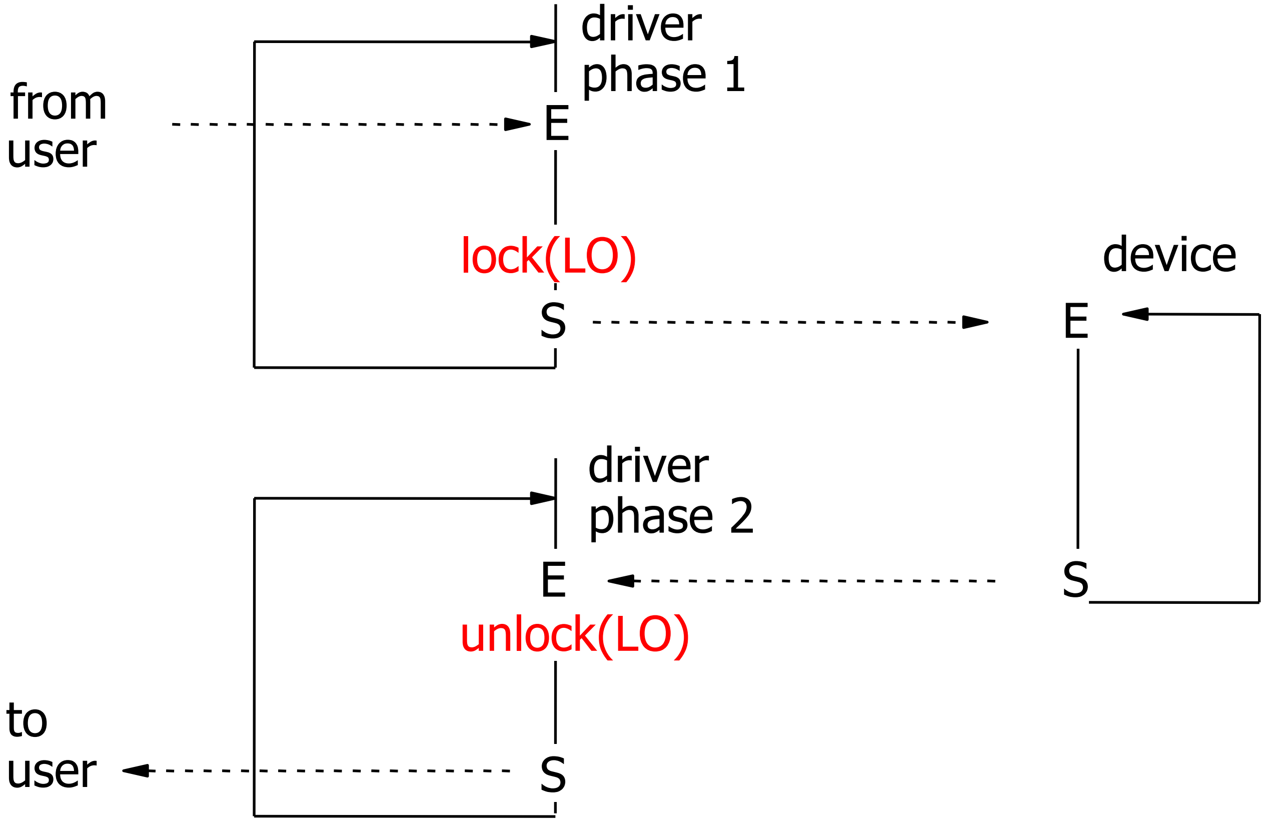
- We can reduce this latency if the driver prepares the next request during the time, when the device is processing the current request.
- To achieve this, the work has to be organized such that parallelism between device and driver is possible.



- The solution is the driver's decomposition into two phases, where the first creates new requests and the second is responsible for progress analysis.

Two-Phase-Driver

- The access to device specific data (registers) is then a critical section that needs to be put under mutual exclusion (locking).
- It is also recommended to give the first driver phase higher priority (with preemption) to make sure that after releasing the lock the next request can be submitted immediately.



Read-ahead

- Read more than currently requested
  - In assumption the next sectors or blocks will be requested soon.
  - Reading of next sectors or blocks with small cost.
- Buffering of not yet requested blocks
  - Device cache
  - Buffer cache in main memory
- Not appropriate for writing!
  - Write back caches

8.5.2 Solid State Drives (SSDs)

- SSDs use integrated circuit assemblies as memory to store data persistently
- SSDs do not employ moving mechanical components
  - Shock and vibration resistant
- Non-Volatile NAND-based flash memory commonly used, however SSDs can be constructed from RAM but need additional precautions against power loss
- SSDs are available in the form factor of HDDs in both physical appearance and connectivity
  - HDDs can be easily replaced by SSDs

HDDs vs. SSDs

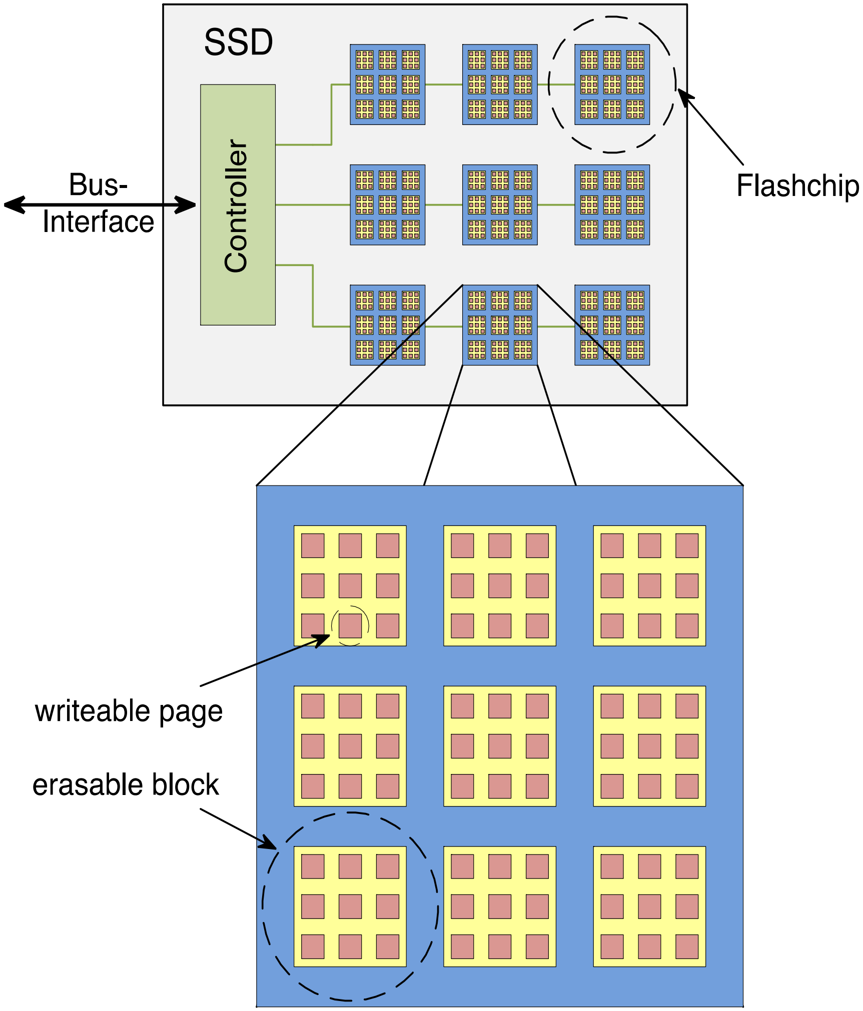
Property	HDD	SSD
Random access time	2.9ms to 12ms	<0.1ms
Start-up time	Several seconds (disk spin-up)	Almost instantaneous
Read latency time	Different for every different seek	Generally low
Data transfer rate	~140 MB/s	100-600 MB/s (Highest-End several GB/s)
Read performance	Depends on required number of seeks	Consistent on whole SSD
Fragmentation	Problematic due to additional seeks	No Problem
Noise	Can be significant	(almost) none
Cost per capacity	<$0.10 per GB	>$0.50 per GB
Number of writes	~10^{10} per sector	~10^{4}-10^{6} per block

Physical Assembly of SSDs

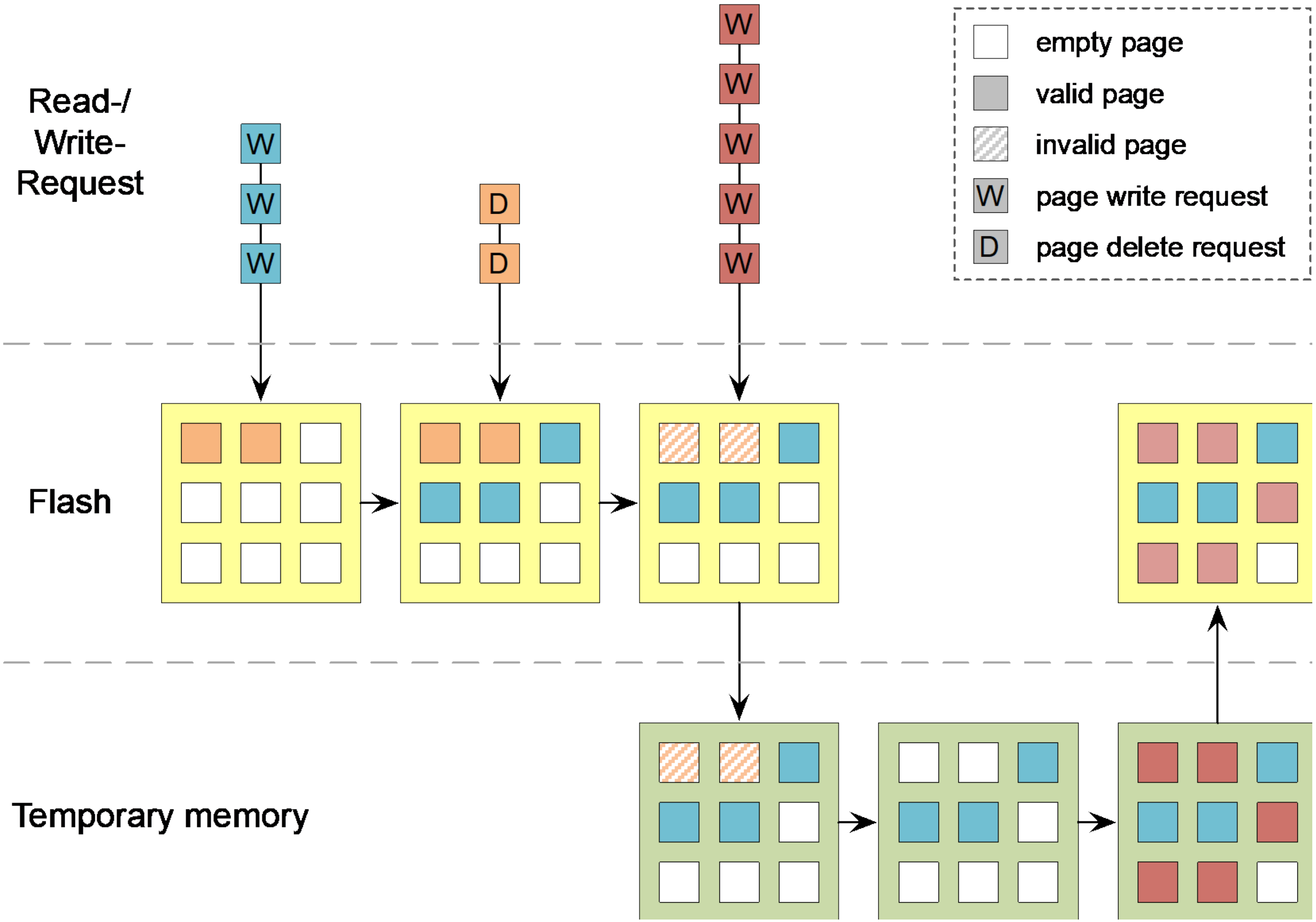
- (logical block addresses) are mapped to flash pages by a controller

- Flash pages can be reassigned to different LBAs

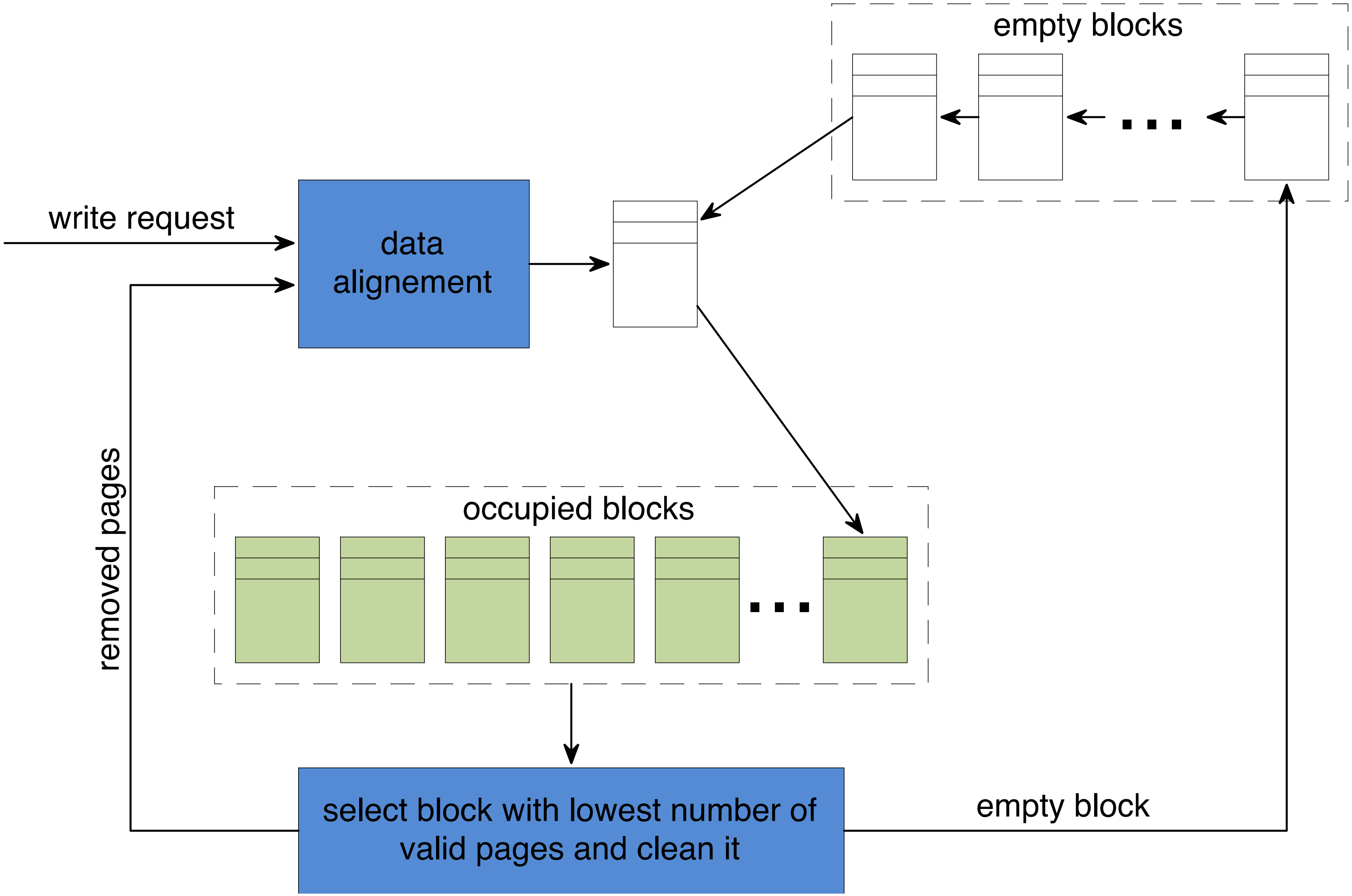
- Only blocks of ~64-128 pages are erasable



No Updates In-Place



Garbage Collection



Wear leveling

- Flash blocks wear out by writing to them
- Some flash blocks may reach their end of life much earlier than others
- Wear leveling distributes all write accesses over the medium

- Dynamic wear leveling
  - LBAs are initially mapped to a certain flash block
  - LBAs are mapped to a different flash block as soon as they are rewritten

- Static wear leveling
  - Additionally to dynamic wear leveling blocks are relocated and remapped when they are not written for a certain time

Write Amplification

- Write Amplification is a phenomenon where the actual amount of physical information written is a multiple of the logical information written

$$\text{write amplification} = \frac{\text{data written to the (flash) memory}}{\text{data written by the host}}$$

- Write Amplification gets increased by
  - Wear leveling
  - Random writes
- Write Amplification can be reduced by
  - Garbage collection
  - Over-provisioning
  - TRIM

Sustaining write performance

- Random write performance of an SSD is influenced by the workload history of the SSD.

- Main factor is the number of available empty pages in the SSD.

- The number of available empty blocks can be increased by
  - Spare capacity
    - total capacity = spare capacity + usable capacity
    - A number of blocks that will never be used
    - Enforced by the SSD controller (spare capacity not visible for OS)
    - Enforced by the OS (spare capacity not visible for user)
  - TRIM
    - TRIM is an ATA-Command that informs the device of invalid sectors
    - Allows an SSD to garbage collect blocks before their mapped sectors are rewritten

Flash in embedded/mobile devices

- Embedded CPUs are normally equip with or connected to flash memory similar to the flash memory in SSDs
    - Ranging from several kB e.g. in small 8-Bit controllers
    - To several GB e.g. in smart phones
- Flash memory is directly connected to the CPU – No controller!
- Most of the tasks of the SSD controller have to be done by the OS
    - Flash-Page mapping
    - Garbage collection
    - Wear leveling

8.6 RAID

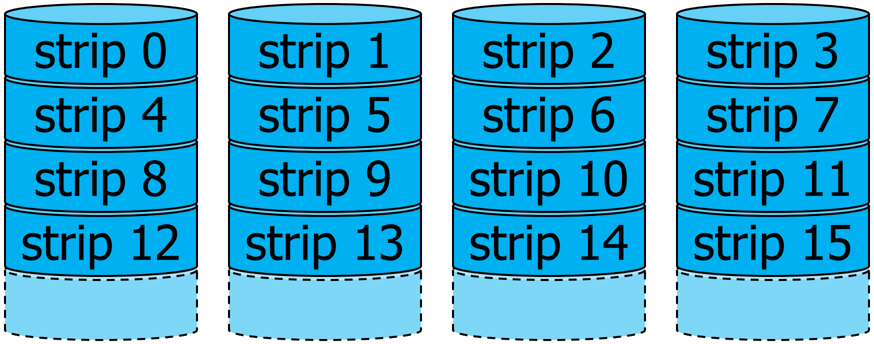
- Access time for hard disks did not improve much compared to processor cycle times.
- The discrepancy of 6 orders of magnitude (msec vs. nsec) is still a significant performance obstacle.
- At the same time capacities have increased and costs plummeted.
- Therefore the questions arises how we can get a performance benefit by using parallelism of inexpensive disks.
- RAID (Redundant Array of Independent Disks) is a standardized schema to organize file systems on several disks.
- Originally, RAID referred to „Redundant Array of **Inexpensive** Disks".

RAID

- Large numbers of disks mean an increased probability of failures.
- RAID has to be realized in fault-tolerant way.
- Properties
  - RAID is a set of physical hard disks, that appear to the user as one device.
  - The data is spread across the physical disks.
  - Redundant disk capacity may be used to store parity bits.
- RAID (originally) distinguishes 6 different schemes (RAID Level 0-5), later extended (RAID Level 6, combined levels such as 1-0 or 0-1)
- Fault model:
  If a block is requested, the disk delivers the correct block (fault free case) or an error message (in case of fault).
  RAID does not detect data corruption caused by disk (exception: RAID level 2 due to error correcting code) but relies on detection at level of disk (usually done by error correcting codes).

RAID Level 0 („non redundant“)

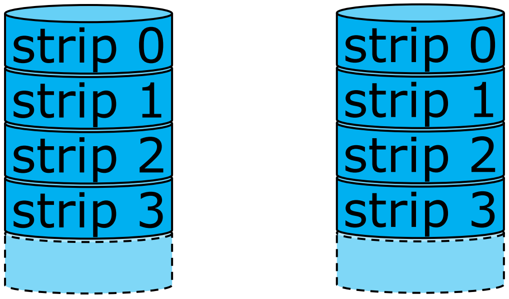
- Data organized in „Strips“ (e.g. sectors or blocks)
- Strips are distributed around on the disks.
- An I/O request consisting of different strips can be processed in parallel.
- No redundancy!



strip 0	strip 1	strip 2	strip 3
strip 4	strip 5	strip 6	strip 7
strip 8	strip 9	strip 10	strip 11
strip 12	strip 13	strip 14	strip 15

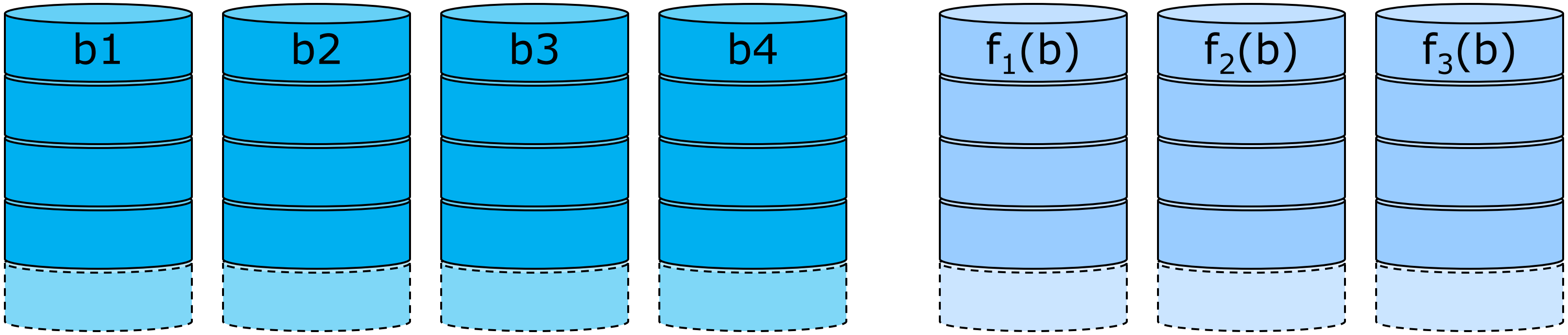
RAID Level 1 („mirrored“)

- Fault tolerance by complete mirroring of all data.
- Costly, since double capacity required.



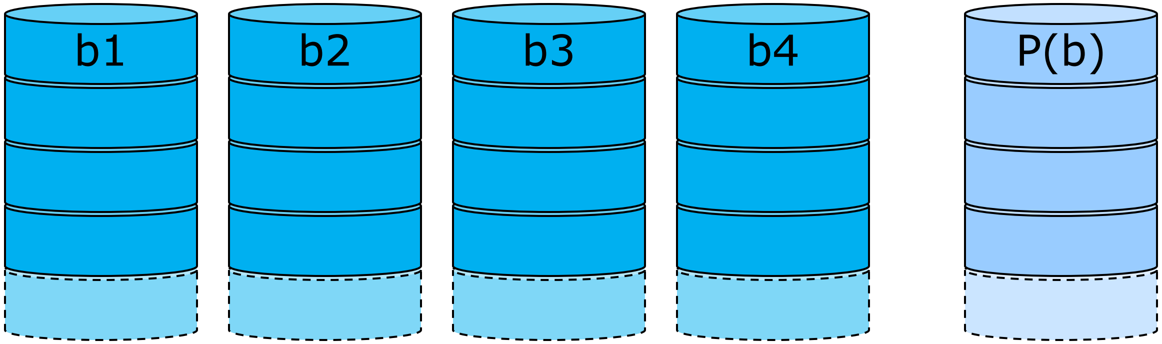
RAID Level 2 („Error Correcting Code")

- Strips are small compared to RAID-0 or RAID-1.
- Typically bits or bytes.
- Error correcting codes (e.g. Hamming Codes) are calculated and stored on redundant disks.
- The number of redundant disks grows logarithmically with the number of disks.
- Disks need to be synchronized.
- Never used in commercial application.



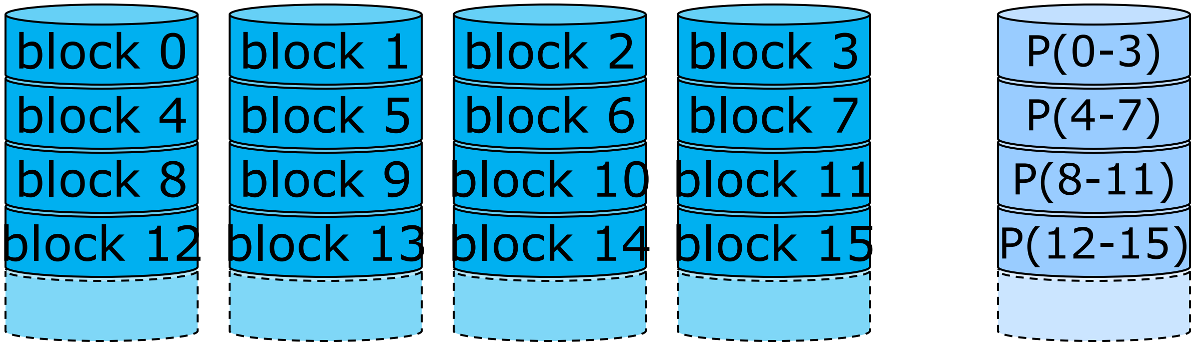
RAID Level 3 („bit-interleaved parity")

- Since we usually do know, which disk device has failed, we can use simple parity bits instead of Hamming-Codes.
- Only one redundant disk to store the parity bits is needed.



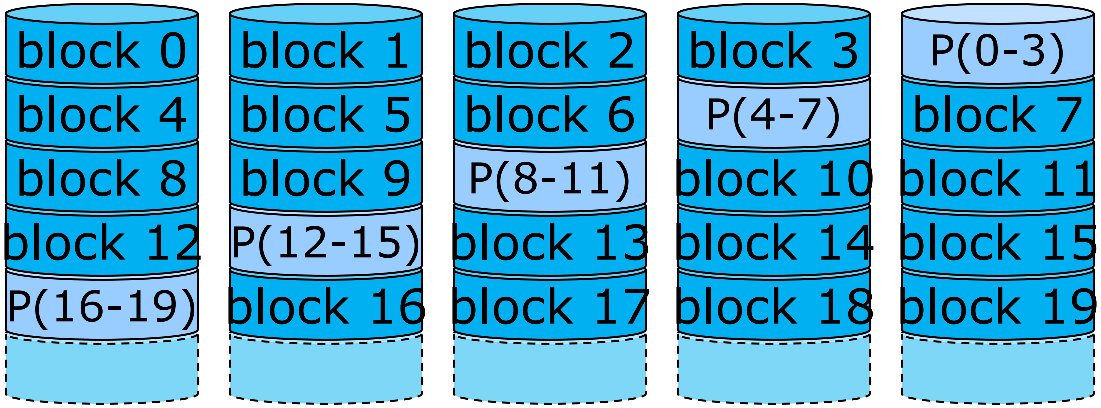
RAID Level 4 („block-interleaved parity“)

- Like RAID Level 3, but with strips of block size
- Only one redundant disk to store parity bits required.
- Since each write operation needs to access the parity disk, there is a danger of a bottleneck.
- No disk synchronization needed.



RAID Level 5
(„block distributed parity")

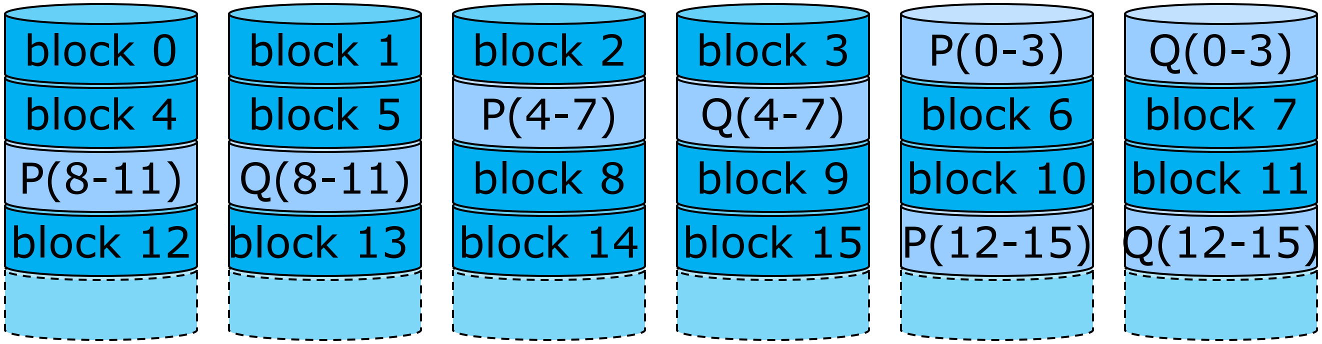
- Like RAID Level 4, but distribution of parity data across all disks
- Avoids bottleneck.



block 0	block 1	block 2	block 3	P(0-3)
block 4	block 5	block 6	P(4-7)	block 7
block 8	block 9	P(8-11)	block 10	block 11
block 12	P(12-15)	block 13	block 14	block 15
P(16-19)	block 16	block 17	block 18	block 19

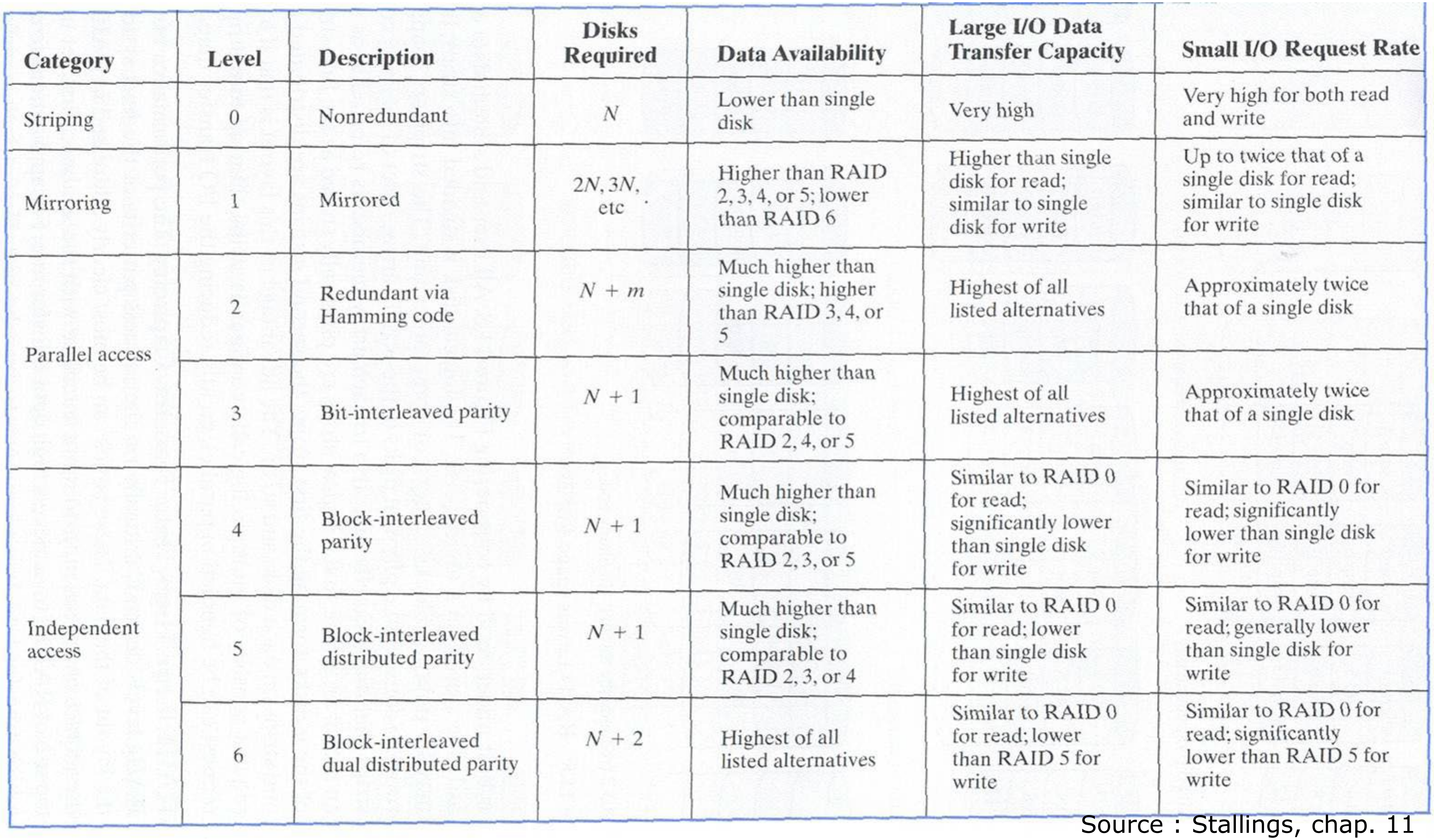
RAID Level 6 („dual redundancy“)

- RAID Level 5 can tolerate one failed disk at most.
- RAID Level 6 works with two independent checksum systems (P,Q) and can tolerate up to two disk failures.
- Parity information is stored in a distributed way like RAID Level 5.



block 0	block 1	block 2	block 3	P(0-3)	Q(0-3)
block 4	block 5	P(4-7)	Q(4-7)	block 6	block 7
P(8-11)	Q(8-11)	block 8	block 9	block 10	block 11
block 12	block 13	block 14	block 15	P(12-15)	Q(12-15)

RAID Comparison



Category	Level	Description	Disks Required	Data Availability	Large I/O Data Transfer Capacity	Small I/O Request Rate
Striping	0	Nonredundant	N	Lower than single disk	Very high	Very high for both read and write
Mirroring	1	Mirrored	$2N$, $3N$, etc	Higher than RAID 2, 3, 4, or 5; lower than RAID 6	Higher than single disk for read; similar to single disk for write	Up to twice that of a single disk for read; similar to single disk for write
Parallel access	2	Redundant via Hamming code	$N + m$	Much higher than single disk; higher than RAID 3, 4, or 5	Highest of all listed alternatives	Approximately twice that of a single disk
	3	Bit-interleaved parity	$N + 1$	Much higher than single disk; comparable to RAID 2, 4, or 5	Highest of all listed alternatives	Approximately twice that of a single disk
Independent access	4	Block-interleaved parity	$N + 1$	Much higher than single disk; comparable to RAID 2, 3, or 5	Similar to RAID 0 for read; significantly lower than single disk for write	Similar to RAID 0 for read; significantly lower than single disk for write
	5	Block-interleaved distributed parity	$N + 1$	Much higher than single disk; comparable to RAID 2, 3, or 4	Similar to RAID 0 for read; lower than single disk for write	Similar to RAID 0 for read; generally lower than single disk for write
	6	Block-interleaved dual distributed parity	$N + 2$	Highest of all listed alternatives	Similar to RAID 0 for read; lower than RAID 5 for write	Similar to RAID 0 for read; significantly lower than RAID 5 for write

Source : Stallings, chap. 11

Further Reading

- Stallings,W.: Operating Systems 6th ed., Prentice Hall, 2008, Chapter 11
- Rubini, A.: Linux Device Drivers, 3rd ed. O'Reilly, 2005
- Nutt,G.: Operating Systems, Addison Wesley, 2000, Chapter 5
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- Iyer,S.; Druschel,P.: Anticipatory scheduling: A disk scheduling framework to overcome deceptive idleness in synchronous I/O. 18th ACM SOSP 2001