Operating Systems

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IX. Input/Output
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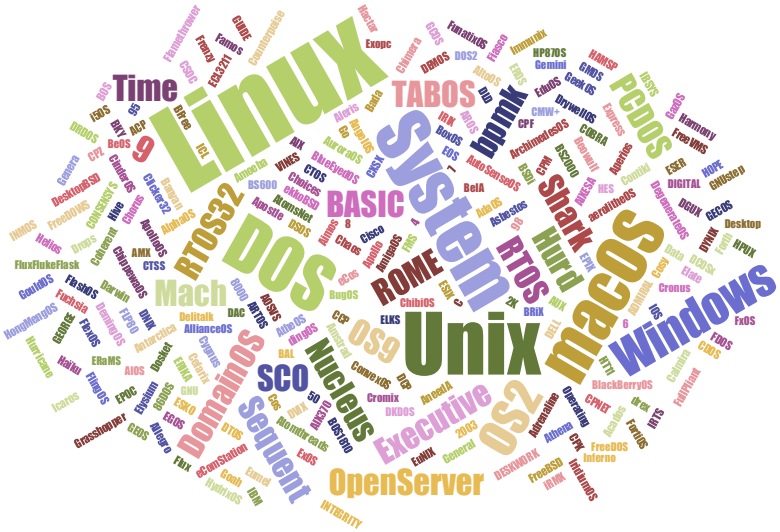
RUB Faculty of Computer Science
RUHR UNIVERSITÄT BOCHUM RUB
www.informatik.rub.de
Chair of Operating Systems and System Software

Agenda

- Recap
- Organizational Matters
- Input/Output Hardware
  - Interconnects
  - Device Classes
  - Interrupts, Direct Memory Access
- Device Programming
  - Address Space
  - Operating Modes
- Input/Output in Operating Systems
  - Input/Output Abstractions in UNIX
  - Buffered Input/Output
- Summary and Outlook



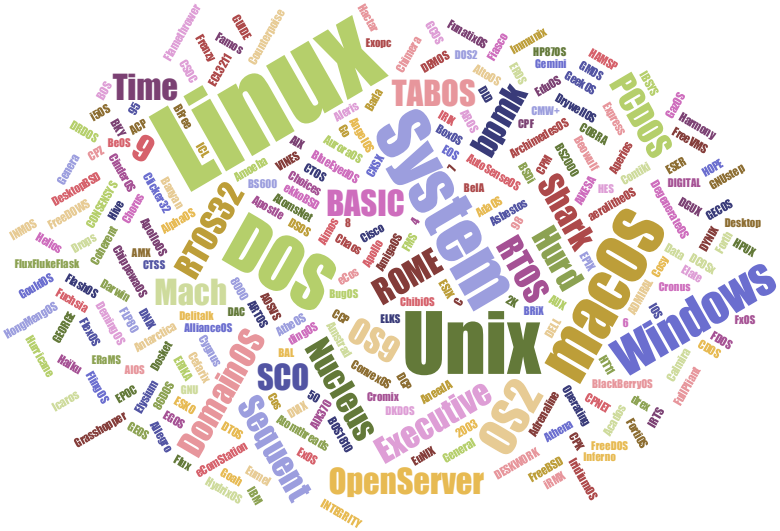
Literature References

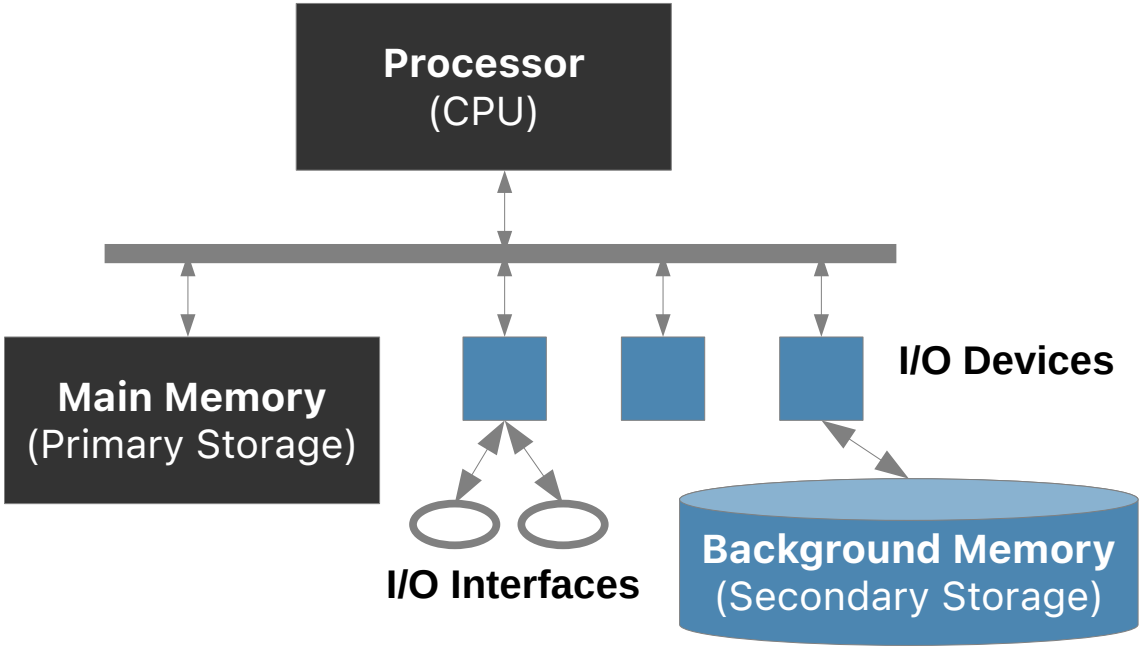
Silberschatz, Chapter 12

Tanenbaum, Chapter 5

Recap

- file systems: operating system abstraction to organise persistent data on storage devices
- mapping of logical view (files, directories) to physical view (blocks)
- consider hardware properties for efficient data management
  - head positioning
  - wear leveling
- reliability by redundancy, better performance with copy-on-write





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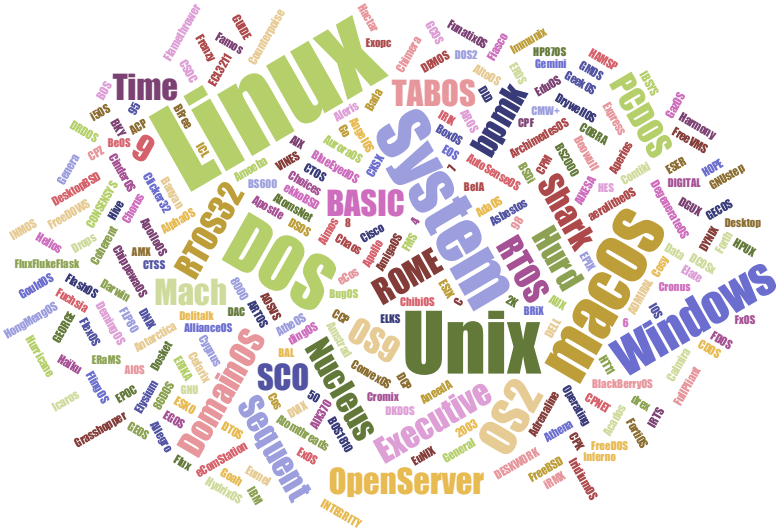
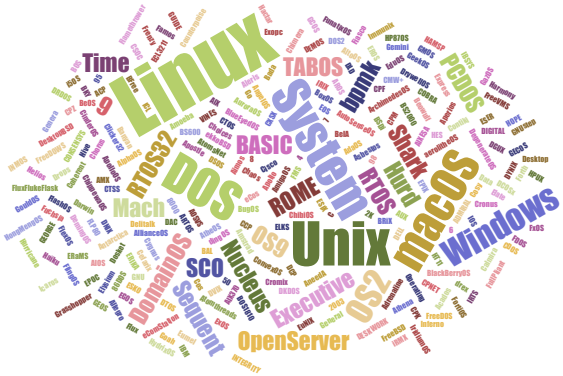


Organizational Matters



- lecture
  - Wednesday, 10:15 – 11:45
  - format: synchronous, **hybrid**

    → in presence (Room HID, Building ID)

    → online lecture (Zoom)
  - **exam:** August 7, 2023 (first appointment)
    September 25, 2023 (retest appointment)
- exercises: **group allocation ~~almost~~ complete**
  - make use of group work - for your own benefit!
- manage course material, asynchronous communication: Moodle
- `https://moodle.ruhr-uni-bochum.de/course/view.php?id=50698`

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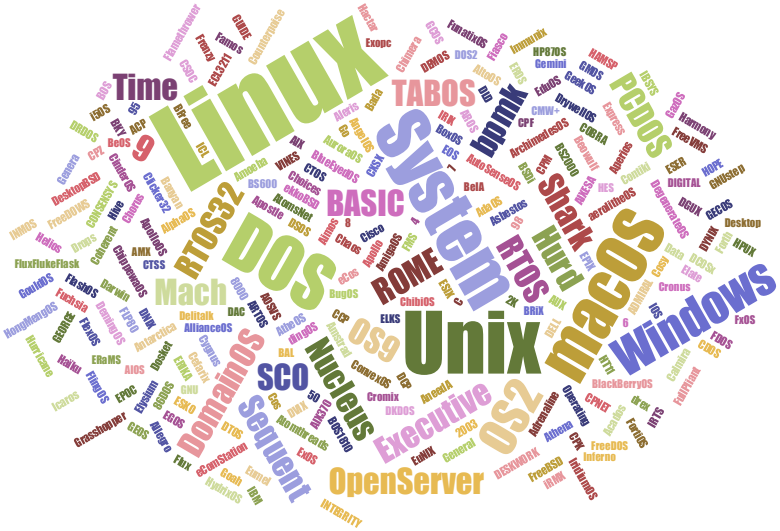


Interconnects of I/O Devices

keyboard controller | video controller | HDD/SSD controller | network controller

bus

CPU | main memory

- input/output devices are connected to the system bus via controllers
- programming is done via I/O registers on the controllers

Example: PC Keyboard

- serial communication, character-based
  - keyboards are complex and have own (embedded) processors

make and *break* codes for pressed keys

control codes, for example switch LEDs on/off

keyboard controller

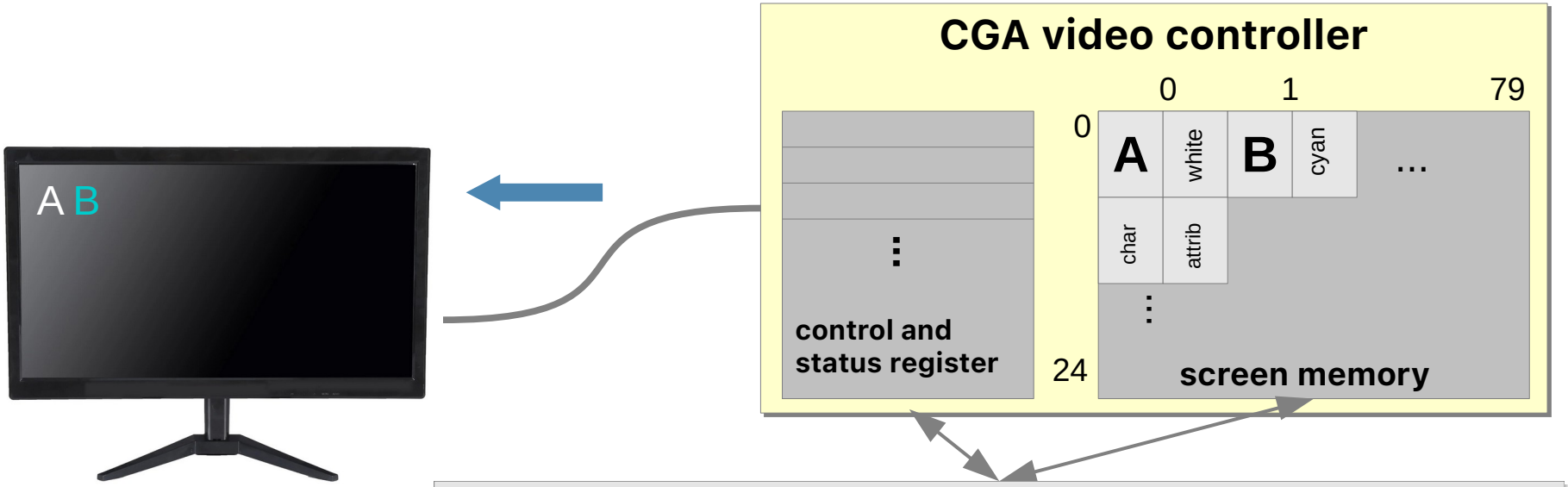
as soon as a character is ready for retrieval, a keyboard controller issues an **interrupt request** (IRQ)

software tasks

- initialise keyboard controller
- retrieving characters from the keyboard
- mapping of the make and break codes to ASCII/UTF-8
- sending (control) commands

Example: CGA Video Controller

- communication via video signal
  - converting the screen memory content into an image (80x25 chars)



software tasks

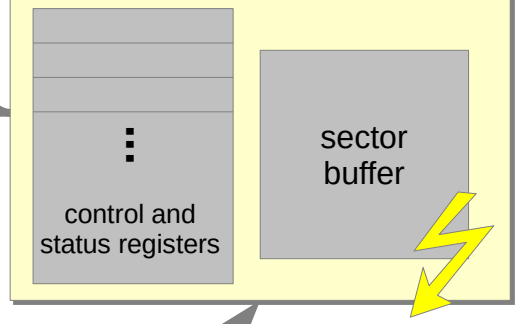
- initialise video controller
- fill screen memory with the desired character codes
- control the position of the cursor
- switch cursor (blinking) on and off

Example: IDE Controller (HDD/SSD)

- communication via AT commands
  - block-based random access to data blocks

AT commands
- calibrate drive
- read/write/verify block
- format track (HDD)
- head positioning (HDD)
- TRIM (SSD)
- diagnostic/health parameters

HDD/SSD controller



data blocks
(512 ... 4096 Bytes)

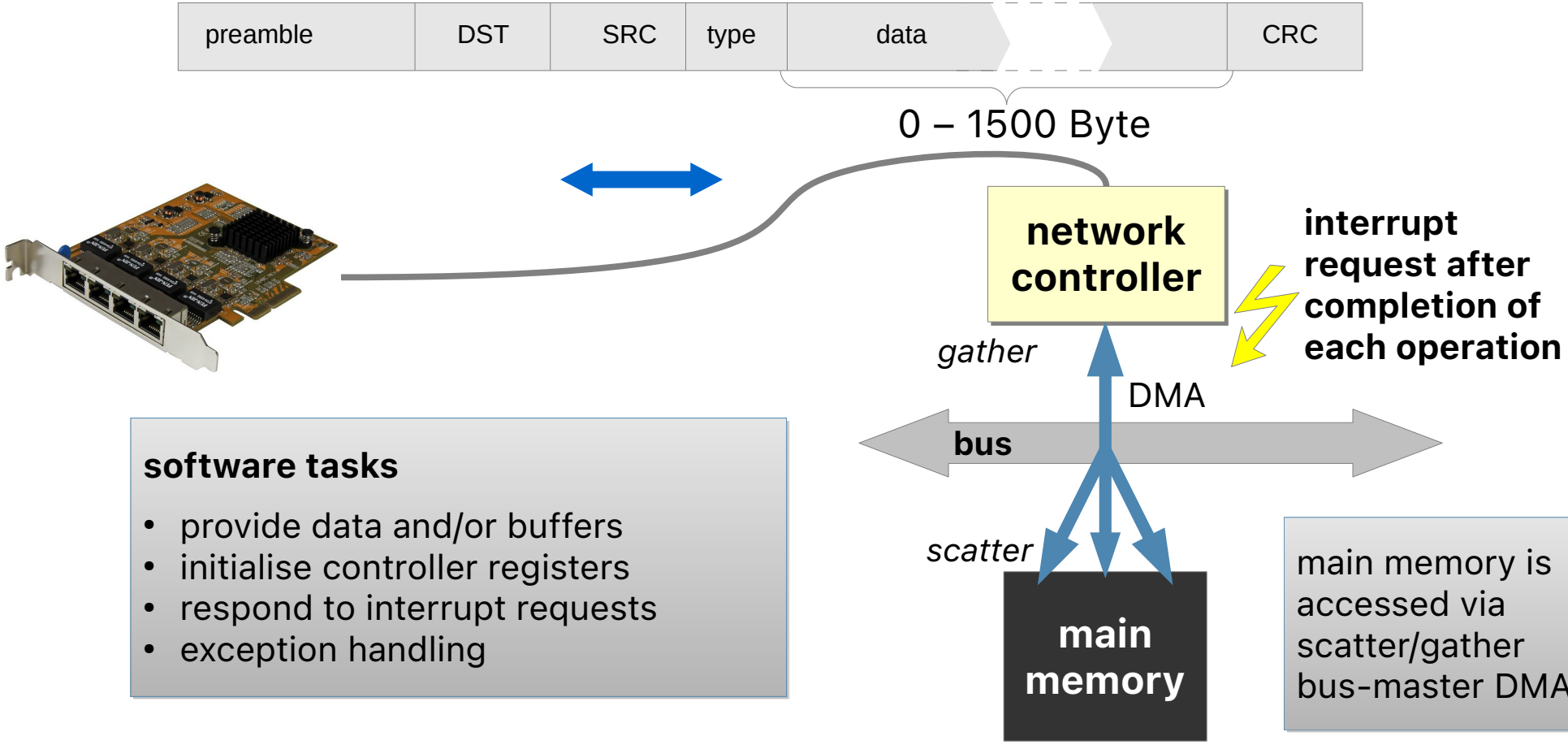
software tasks

- write AT commands to registers
- fill / empty sector buffer
- react on interrupt requests
- exception handling

as soon as the sector buffer has been read or written full, the controller triggers an interrupt request

Example: Network Controller

- serial packet-based bus communication
  - packets have a variable size and contain addresses

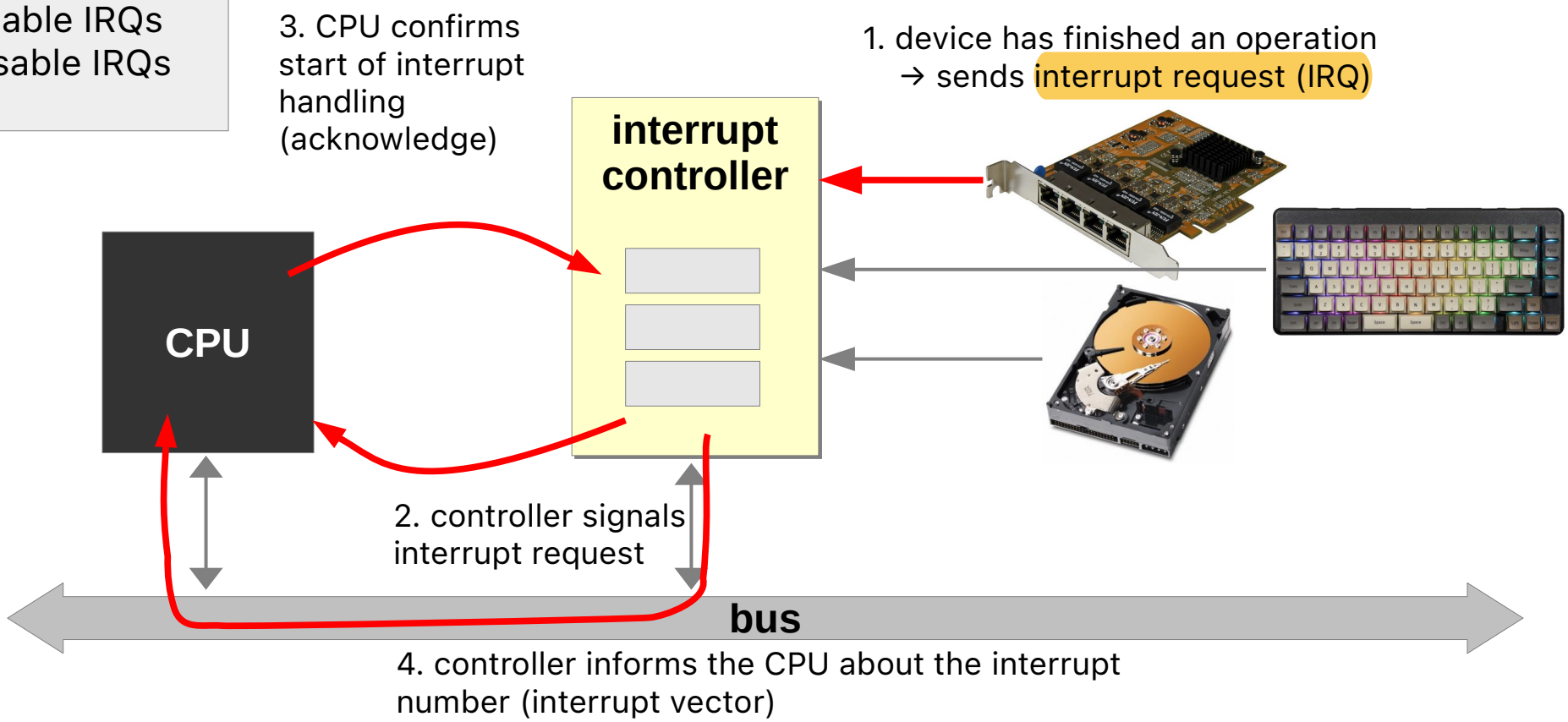


Input/Output - Interrupts

- hardware interrupt requests signal that the software must become active

software can suppress IRQ handling:
sti → enable IRQs
cli → disable IRQs

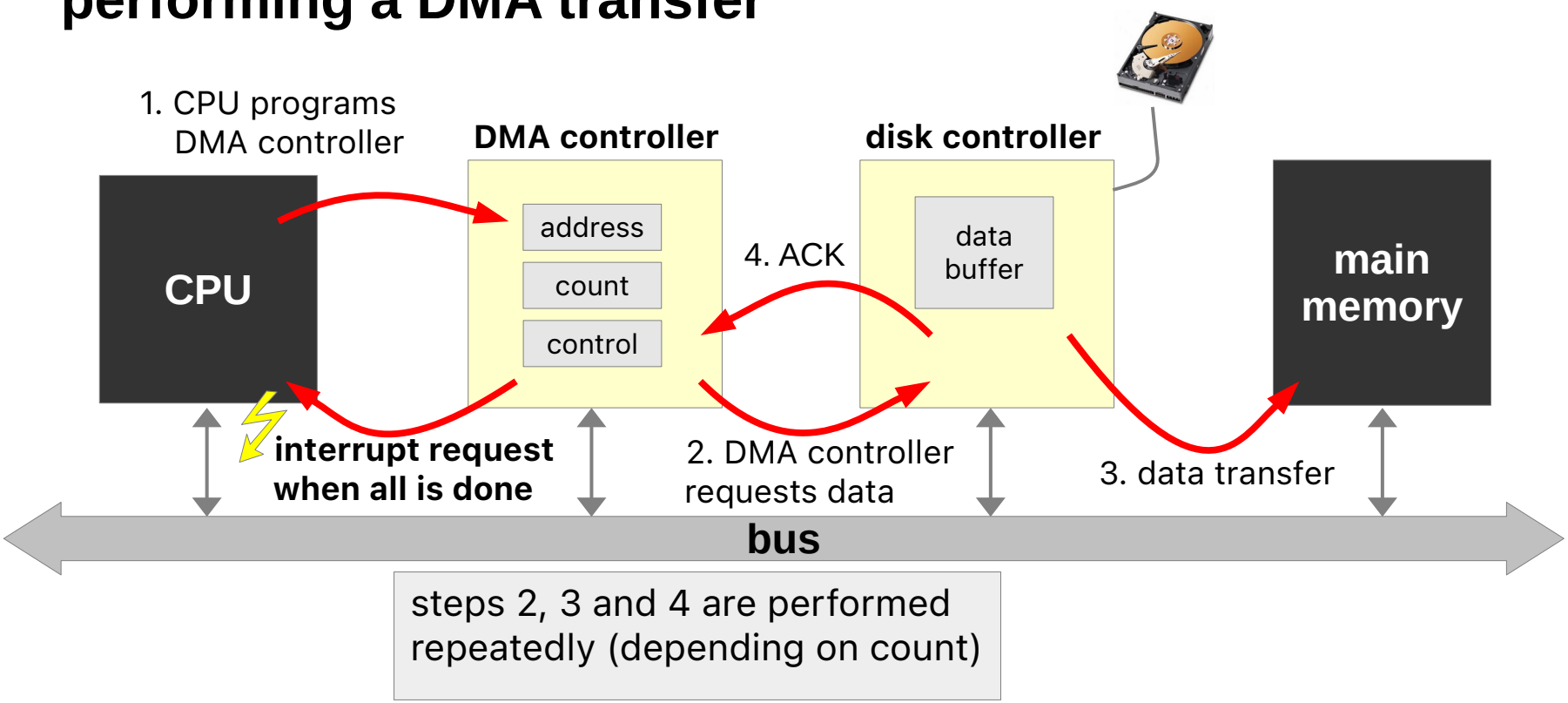
sequence of an interrupt handling on the hardware level



Input/Output - Direct Memory Access (DMA)

- DMA is used by complex controllers to transfer data to and from main memory independently of the CPU

performing a DMA transfer



Device Classes

- **character-oriented devices**
  - keyboard, touch screen, printer, modem, mouse, etc.
  - mostly: purely sequential access, rarely random positioning
- **block-oriented devices**
  - hard disk (e.g., HDD), flash memory (e.g., SSD), optical disk drives
  - mostly: random block access (random access)
- other devices do not easily fit into the above scheme
  - graphics cards (especially 3D acceleration)
  - network cards (protocols, addressing, broadcast/multicast, message filtering, ...)
  - timer modules (one-time or periodic interrupts)

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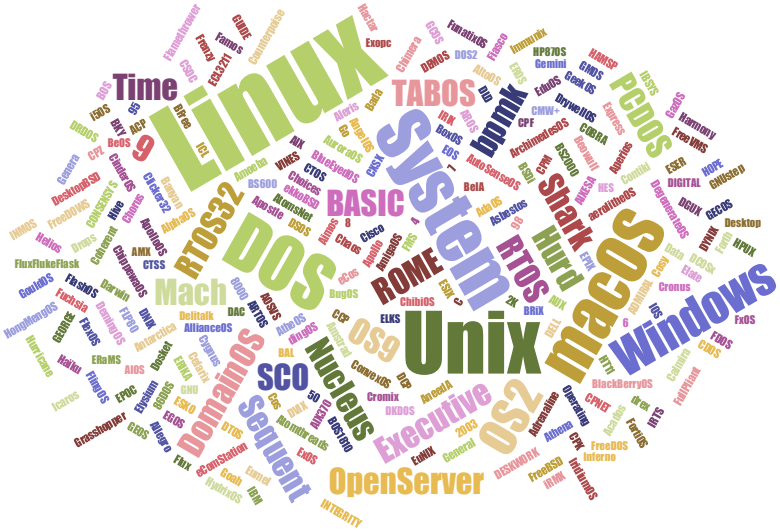
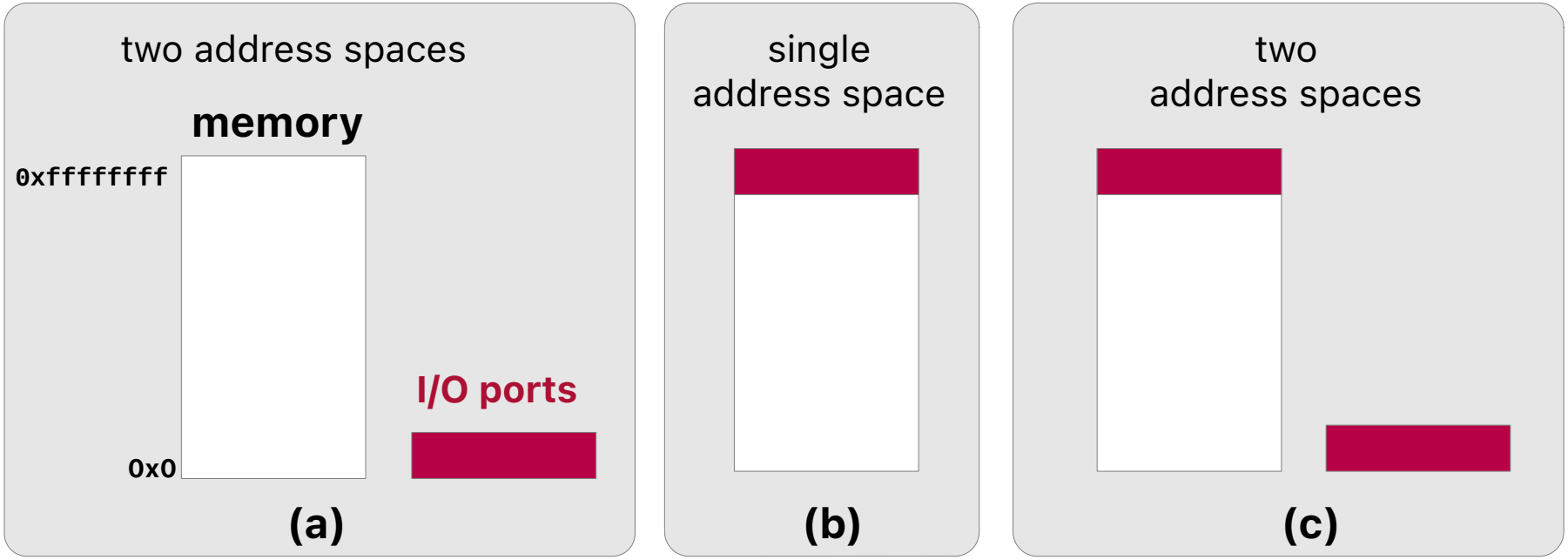


Address Space Models

- register access to I/O device controllers and controller memory is performed depending on the system architecture



(a) separate I/O address space

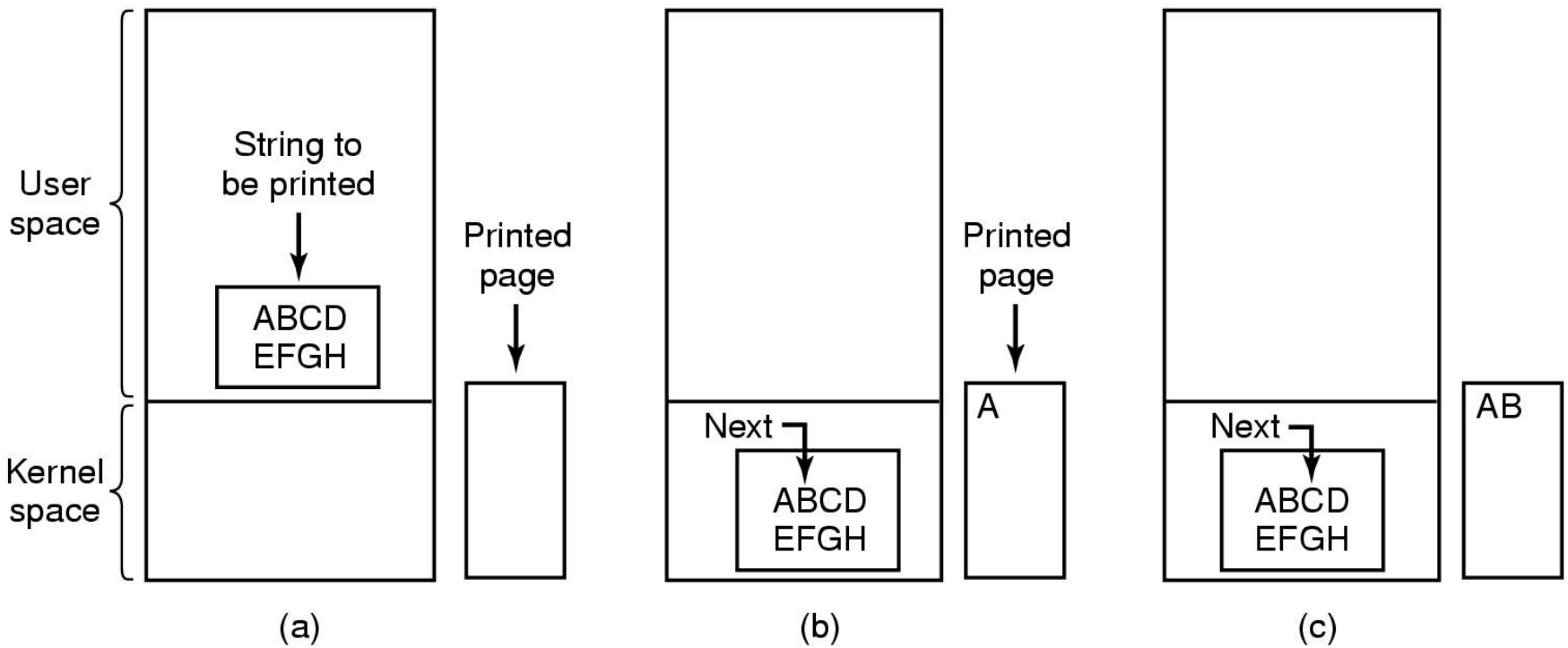
→ addressing using special machine instructions

(b) shared address space (**memory-mapped I/O**)

(c) hybrid architecture

Operating Modes of Device Drivers

- depending on the capabilities of the device, I/O is performed by means of:
  - **programmed input/output** (polling)
  - **interrupts**
  - **direct memory access**
- example: printing a line of text



Source: Tanenbaum, „Modern Operating Systems“

Programmed Input/Output

- **actively waiting** for an input/output device (polling)

```
/* copy character to kernel buffer p */
copy_from_user (buffer, p, count);

/* loop over all characters */
for (i=0; i < count; i++) {

  /* actively wait for printer */
  while (*printer_status_reg != READY);

  /* output one character */
  *printer_data_reg = p[i];
}

return_to_user ();
```

pseudo code of an operating system function for printing text in polling mode

Interrupt-Driven Input/Output

- the CPU can be assigned to another process during the waiting time

```
copy_from_user (buffer, p, count);

/* allow printer interrupts */
enable_interrupts ();

/* wait for printer */
while (*printer_status_reg != READY);

/* output one character */
*printer_data_reg = p[i++];

scheduler ();
return_to_user ();
```

code that initiates the I/O operation

```
if (count > 0) {
  *printer_data_reg = p[i];
  count--;
  i++;
}
else
  unblock_user ();
acknowledge_interrupt ();
return_from_interrupt ();
```

interrupt handling routine

Interrupt-Driven Input/Output - Discussion

- context saving
  - is partly done by the CPU itself, but only the necessary minimum (i.e., status register and return address)
  - all modified registers must be saved and restored at the end of the interrupt handling
- making interrupt handling as short as possible
  - during interrupt handling, further interrupts are usually suppressed
    - ➔ loss of interrupts is imminent
    - ➔ (advanced) interrupt controllers
  - only wake up the process that is waiting for I/O completion, if possible

Interrupt-Driven Input/Output - Discussion

- interrupts are *the* source of asynchronicity
  - root cause of race conditions in the operating system kernel
- interrupt synchronisation
  - simplest possibility: temporarily strictly disable interrupt handling by the CPU while critical sections are being executed
    - x86: `sti`, `cli`
    - again: risk of losing interrupts
  - in practice: multi-stage interrupt handling with minimising the time during which interrupts are strictly disabled
    - UNIX: top half, bottom half
    - Linux: tasklets
    - Windows: deferred procedures

DMA-Driven Input/Output

- the software (i.e., the OS) is no longer responsible for the data transfer between controller and main memory
  - the CPU load is reduced further

```
copy_from_user (buffer, p, count);
set_up_DMA_controller (p, count);
scheduler ();
return_to_user ();
```

code that initiates the I/O operation

```
acknowledge_interrupt ();
unblock_user ();
return_from_interrupt ();
```

interrupt handling routine

DMA-Driven Input/Output - Discussion

- **caches**
  - today's processors operate with data caches; DMA bypasses the cache
  - before setting up a DMA operation, the cache contents must be written back to the main memory and invalidated or the cache must not be used for the corresponding memory region
- **memory protection**
  - today's processors use an MMU to isolate processes and protect the operating system; DMA bypasses memory protection
  - errors in setting up DMA operations are critical
  - application processes must never program DMA controllers directly ➔ use system call(s) instead!

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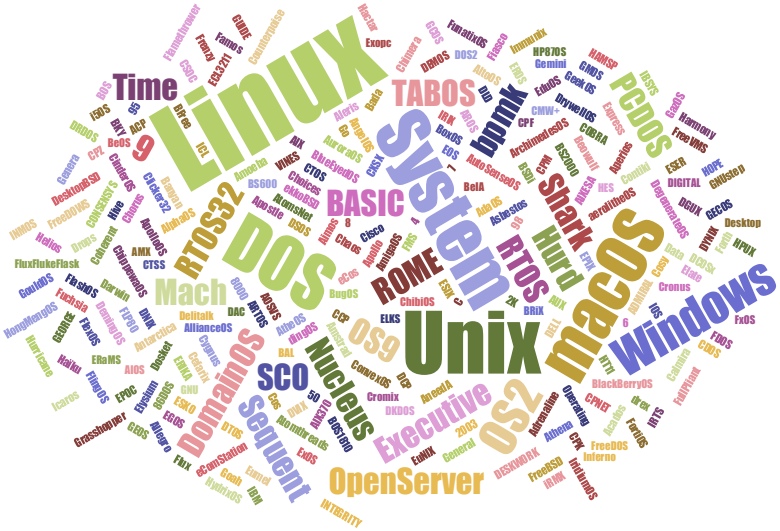
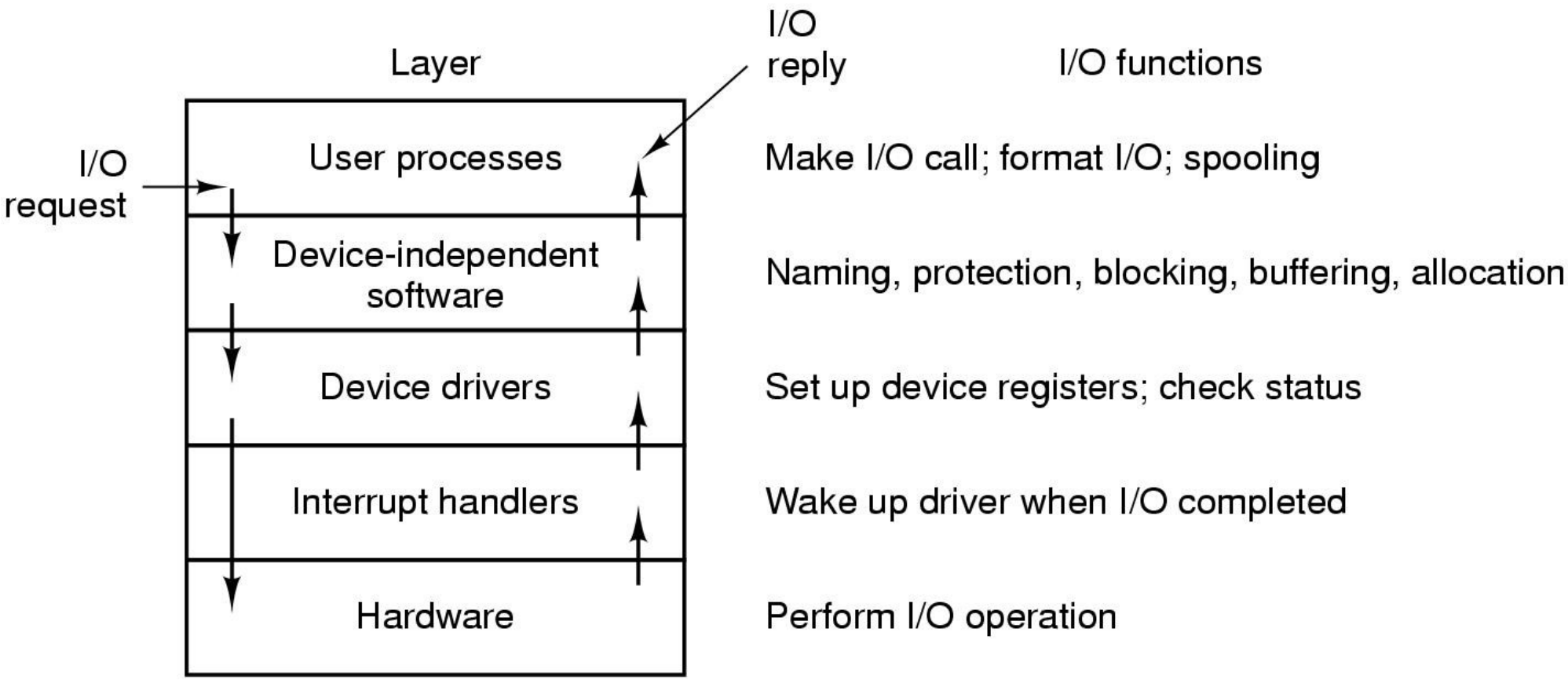


Input/Output Subsystem in Operating Systems



Source: Tanenbaum, „Modern Operating Systems“

Input/Output Device Abstractions in UNIX

- peripheral devices are represented as **special files**
  - devices are used like files using `read(2)` and `write(2)` operations
  - opening the special files creates a connection to the device, which is established by a driver
  - direct access from user space process to the driver
- block-oriented special files (block devices)
- character-oriented special files (character devices)

Input/Output Device Abstractions in UNIX

- unique **description** of I/O devices by a 3-tuple:

  `<device type, major number, minor number>`

- **device type**: block device, character device
- **major number**: driver selection number
- **minor number**: selection of a device within a driver

Input/Output Device Abstractions in UNIX

- extract from the listing of the /dev directory

```
brw-rw---- user disk 3,  0 2023-06-12 14:14 /dev/hda
brw-rw---- user disk 3, 64 2023-06-12 14:14 /dev/hdb
brw-r----- root disk 8,  0 2023-06-12 14:13 /dev/sda
brw-r----- root disk 8,  1 2023-06-12 14:13 /dev/sda1
crw-rw---- root uucp 4, 64 2002-05-02 08:45 /dev/ttyS0
crw-rw---- root lp   6,  0 2023-06-12 14:13 /dev/lp0
crw-rw-rw- root root 1,  3 2006-05-02 08:45 /dev/null
lrwxrwxrwx root root     3 2023-06-12 14:14 /dev/cdrecorder -> hdb
lrwxrwxrwx root root     3 2023-06-12 14:14 /dev/cdrom -> hda
```

access rights

owner

major, minor number

creation time stamp of the special file

name of the special file representing the device

c: character device
b: block device
l: link

Input/Output System Calls in UNIX

- `int open(const char *devname, int flags)`
  - open a device - returns file descriptor as return value
- `off_t lseek(int fd, off_t offset, int whence)`
  - positions the read/write pointer - only for devices with random access
- `ssize_t read(int fd, void *buf, size_t count)`
  - read at max `count` bytes into buffer `buf` from descriptor `fd`
- `ssize_t write(int fd, const void *buf, size_t count)`
  - write `count` bytes from buffer `buf` to descriptor `fd`
- `int close(int fd)`
  - close a device - file descriptor `fd` cannot be used after that

Efficient Waiting for Multiple Devices in UNIX

- until now: blocking read or write calls
- **now**: asynchronous read or write calls
- what to do when reading from multiple sources?

- **solution 1**: non-blocking input/output
  - use O_NDELAY parameter with **`open(2)`**
  - polling operation: process has to call **`read(2)`** repeatedly until data is available
  - works, but is inadequate → CPU time is wasted

Efficient Waiting for Multiple Devices in UNIX

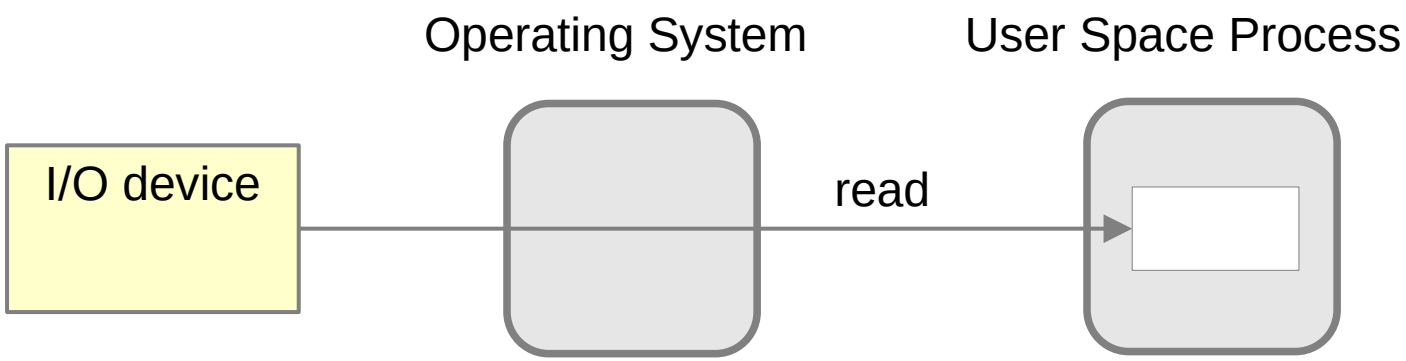
- **solution 2**: simultaneous blocking at multiple file descriptors
  - `select` system call:

```
int select (int nfds, fd_set *readfds, fd_set *writefds,
            fd_set *errorfds, struct timeval *timeout);
```

  - `nfds` specifies up to which file descriptor `select` should operate
  - `read-, write-, errorfds` are file descriptors to wait for:
    - **`readfds`** — until there is data to read
    - **`writefds`** — until data can be written
    - **`errorfds`** — until an error occurs
  - `timeout` determines when the `select` call deblocks at the latest

Input/Output Operations without Buffering

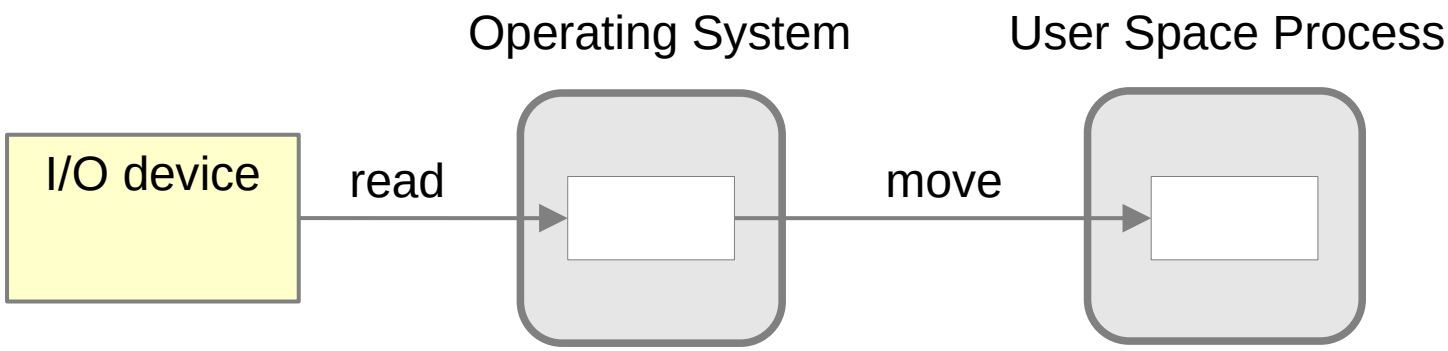
- problems without data buffer in the operating system:
  - data arriving before **`read`** is executed (e.g., from keyboard) would be lost
  - if an output device is busy, **`write`** would have to fail (or block the process) until the device is ready again
  - a process that performs an I/O operation cannot be swapped out



(a) read operation with no buffer

Buffered Input/Output - Single I/O Buffering

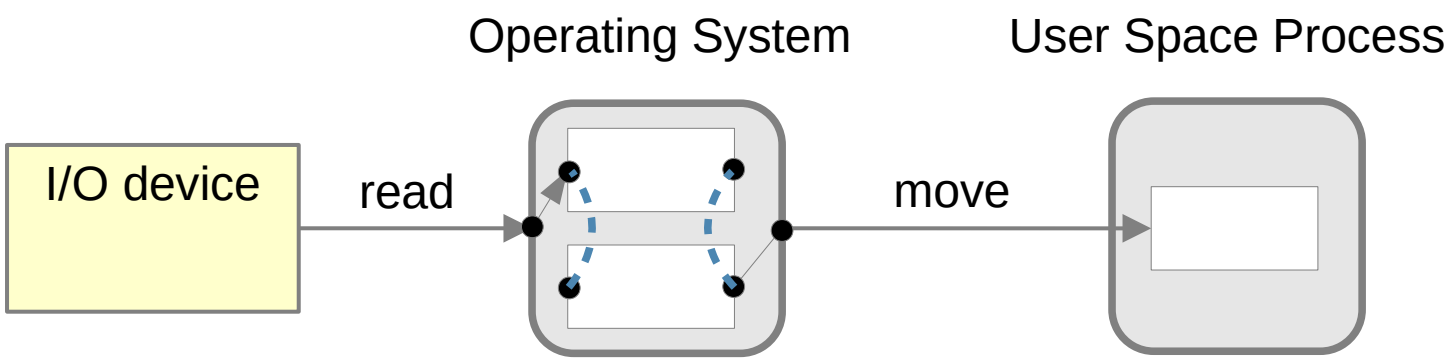
- read
  - system receives data even if the reading process has not yet called read
  - for block devices, the next block can be read ahead while the previous one is being processed.
  - process can be swapped-out, DMA takes place in buffer
- write
  - data is copied, caller is not blocked, data buffer in writer's address space can be reused immediately



(b) read operation with single buffer

Buffered Input/Output - Double I/O Buffering

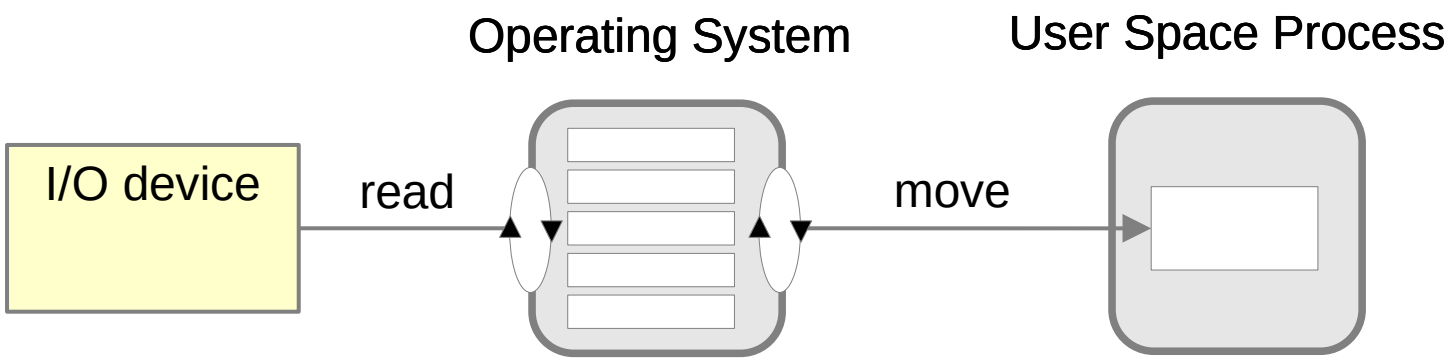
- read
  - while data is being transferred from the I/O device to one buffer, the other buffer's content can be copied to the reader process address space
- write
  - while data is being transferred from one buffer to the I/O device, the other buffer can already be filled with new data from the writer process address space



(c) read operation with double buffer

Buffered Input/Output - Circular I/O Buffering

- read
  - data can be buffered even if the reader process does not make read calls fast enough
- write
  - writer process can make multiple write calls without being blocked



(d) read operation with circular buffer

Buffered Input/Output - Discussion

- buffers decouple I/O operations of processes (user space) from device drivers in the operating system (kernel space)
  - short term: an increased arrival rate of I/O jobs can be managed
  - long term: even with as many buffers as possible, a blocking of processes (or loss of data) cannot be ruled out
- buffers have their price (i.e., resource demand)
  - buffer structure management
  - storage space
  - time overhead for copying data
- in complex systems, buffering spreads across several layers
  - example: layers of network protocols

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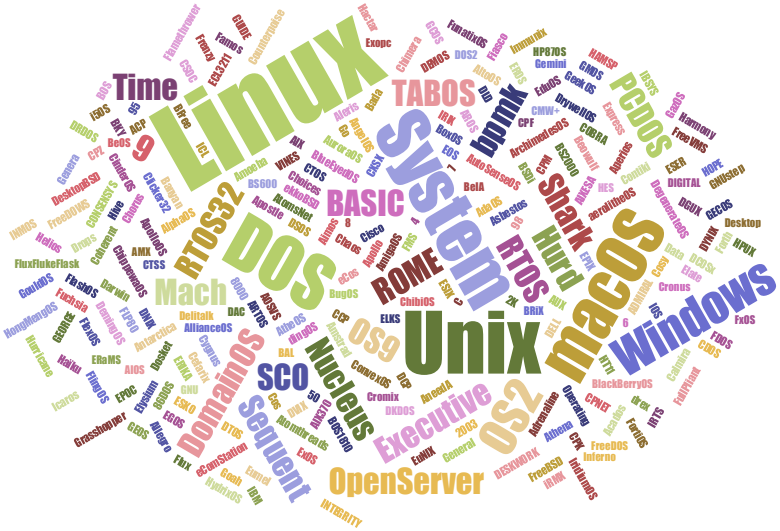

⏭ Summary and Outlook

- **summary**
  - input/output hardware devices are very different and often difficult to handle
  - the art of designing operating systems for efficient inout/output is:
    - ➔ to define uniform and simple interfaces
    - ➔ to handle the heterogenous hardware devices efficiently
    - ➔ to maximize CPU **and** I/O device utilisation
  - device driver diversity is extremely important for wide adaptation of general purpose operating systems
- **outlook: scheduling**
  - methods and strategies to assign CPU time to processes and threads
  - basic and advanced strategies for CPU scheduling

References and Acknowledgments

Lecture

- Systemnahe Programmierung in C (SPiC), Betriebssysteme (Jürgen Kleinöder, Wolfgang Schröder-Preikschat)
- Betriebssysteme und Rechnernetze (Olaf Spinczyk, Embedded Software Systems Group, Universität Osnabrück)

Teaching Books and Reference Book

[1] Avi Silberschatz, Peter Baer Galvin, Greg Gagne: *Operating System Concepts*, John Wiley & Sons, 2018.

[2] Andrew Tanenbaum, Herbert Bos: *Modern Operating Systems*, Pearson, 2015.

[3] Wolfgang Schröder-Preikschat: *Grundlage von Betriebssystemen – Sachwortverzeichnis*, 2023.
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