

ARCOS Group

uc3m | Universidad **Carlos III** de Madrid

Lesson 6

Input/Output Systems

Computer Structure
Bachelor in Computer Science and Engineering



Contents

1. Introduction
2. Buses
 - ▶ Structure and operation
 - ▶ Bus hierarchy
3. Peripheral
 - ▶ Concept and types of peripherals
 - ▶ General structure of a peripheral
 - ▶ I/O modules
4. Case study: hard disk drive and solid-state drives
5. I/O interaction: I/O techniques

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1. Introduction

2. Buses

- ▶ Structure and operation
- ▶ Bus hierarchy

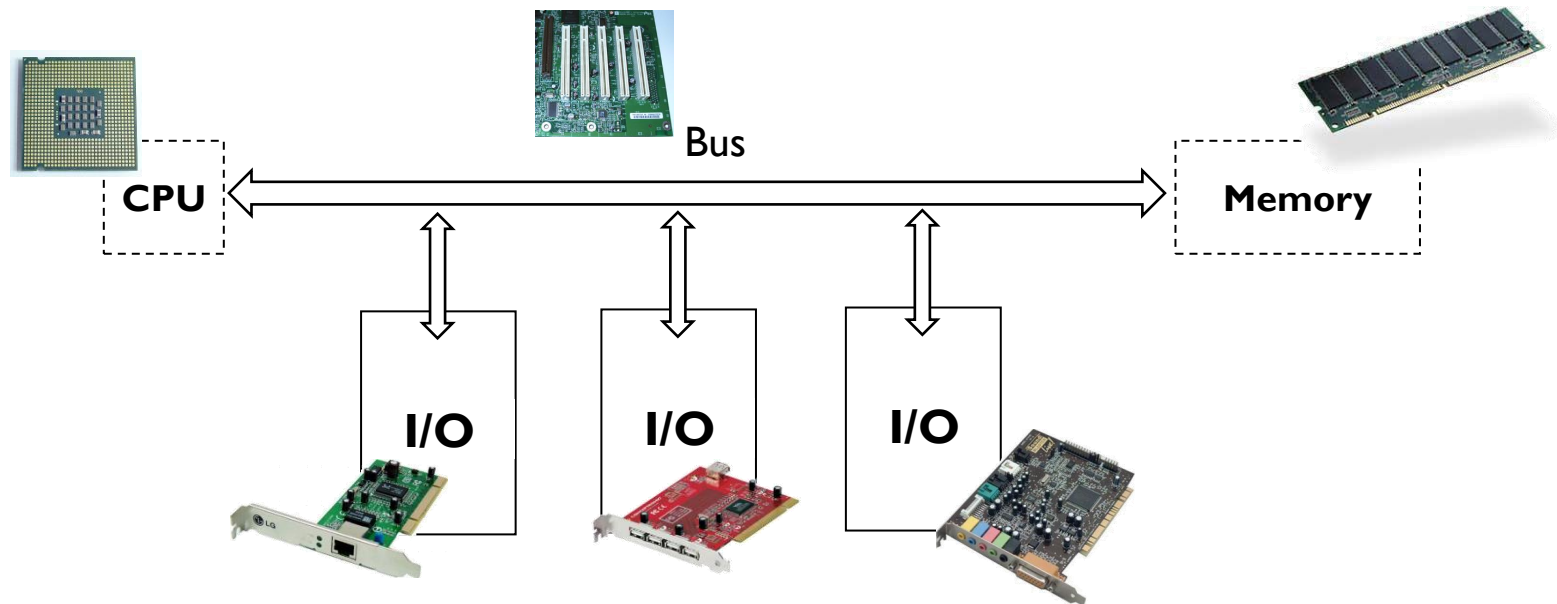
3. Peripheral

- ▶ Concept and types of peripherals
- ▶ General structure of a peripheral
- ▶ I/O modules

4. Case study: hard disk drive and solid-state drives

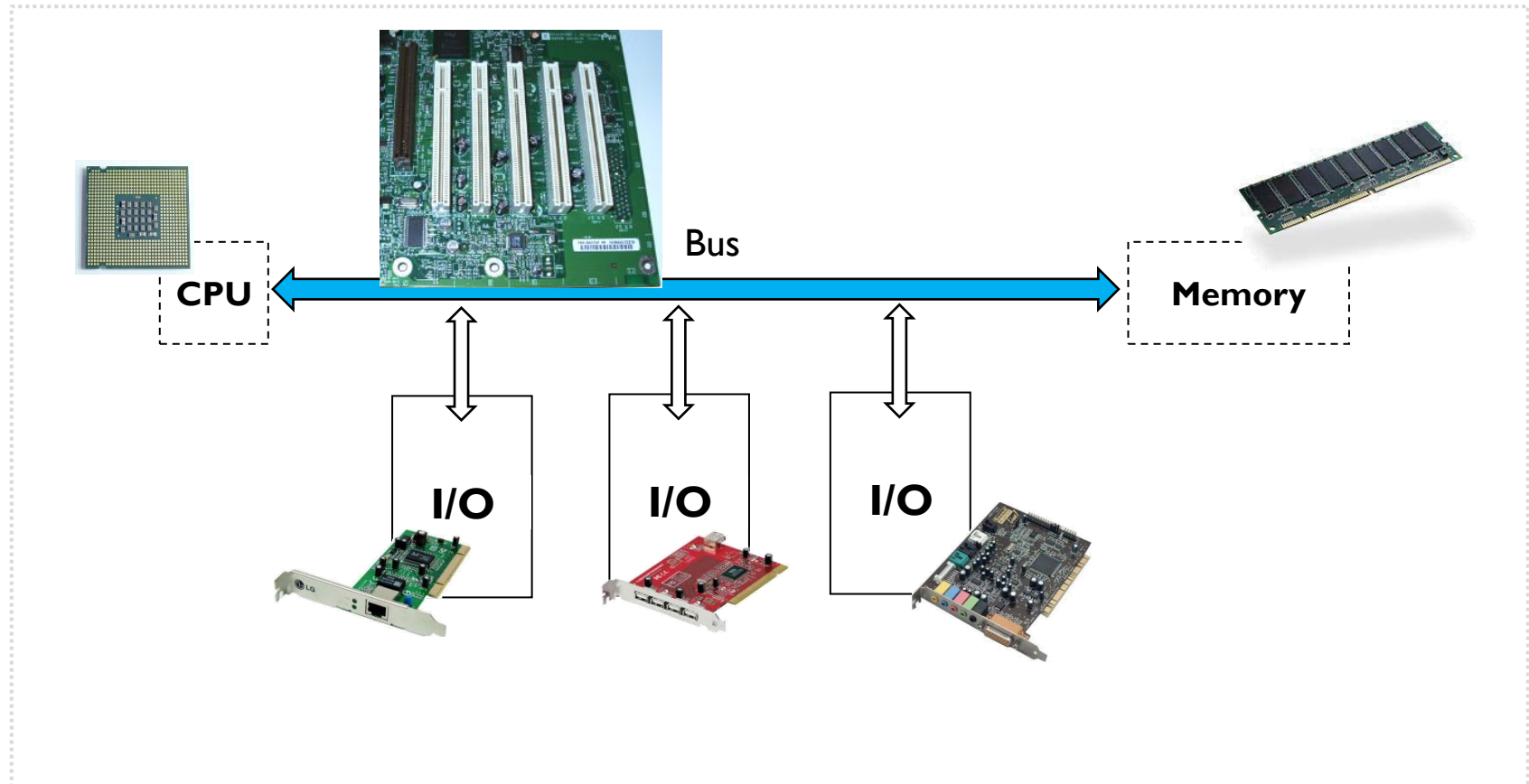
5. I/O interaction: I/O techniques

Introduction



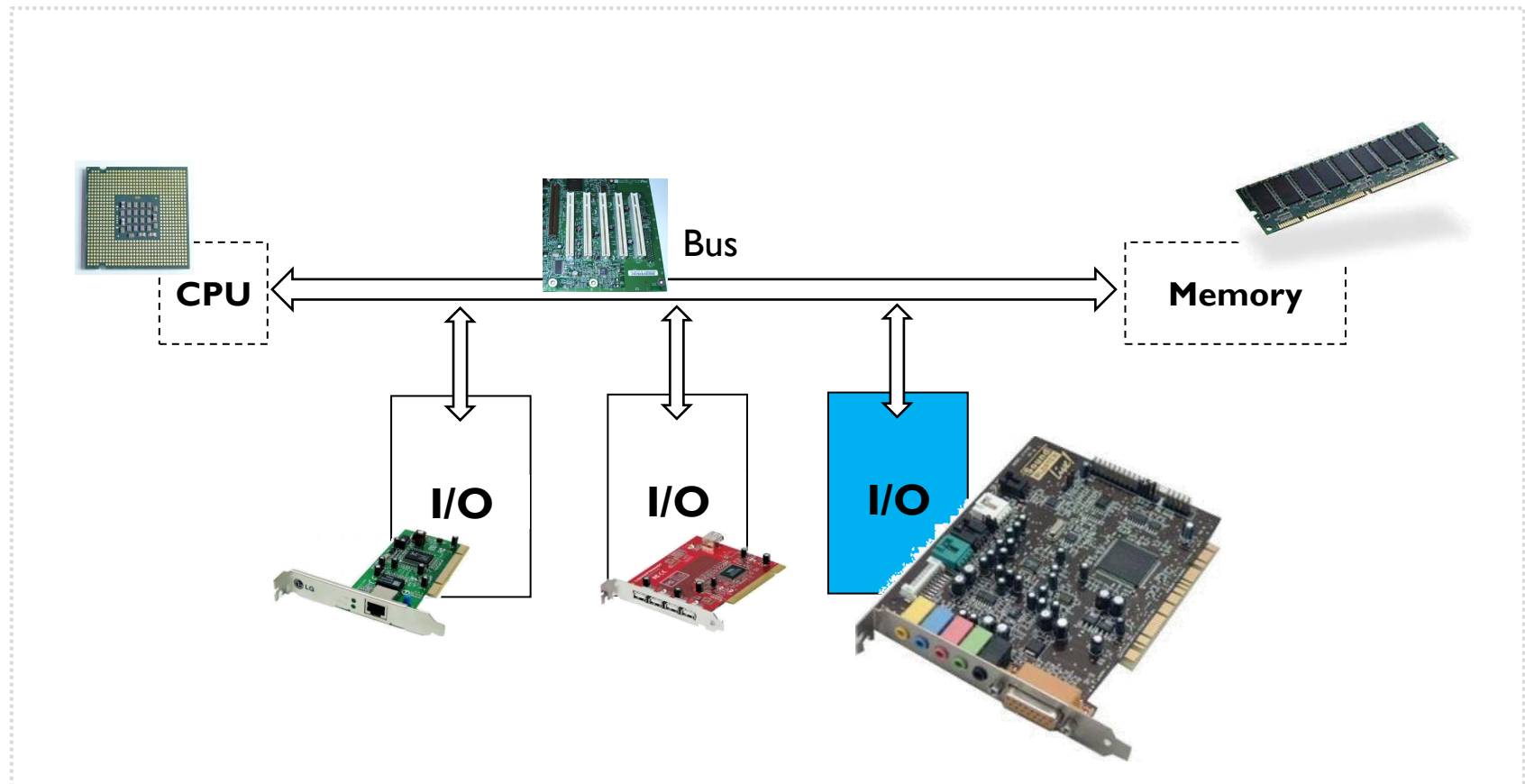
Introduction: bus

- What an interconnection bus is



Introduction: I/O

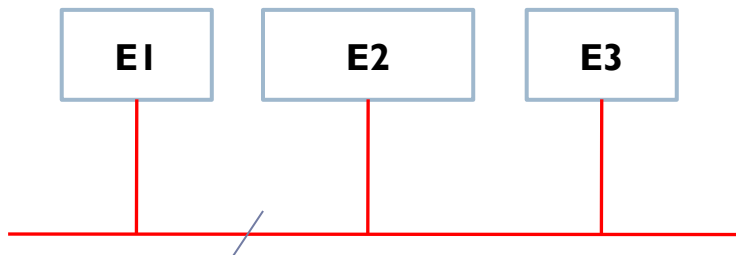
- ▶ What a peripheral is
- ▶ What an input/output module is
- ▶ How data is accessed from peripherals



Contents

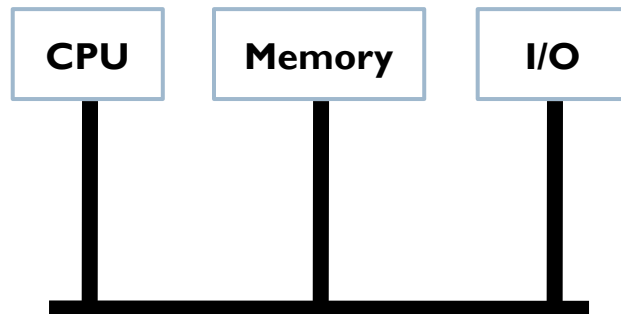
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Bus



- ▶ A bus is a communication **path between two or more devices.**
- ▶ It **consists of several bit transmission lines.**
- ▶ **Shared medium**, univocal.
- ▶ Allows to transmit several bits between two elements connected to it

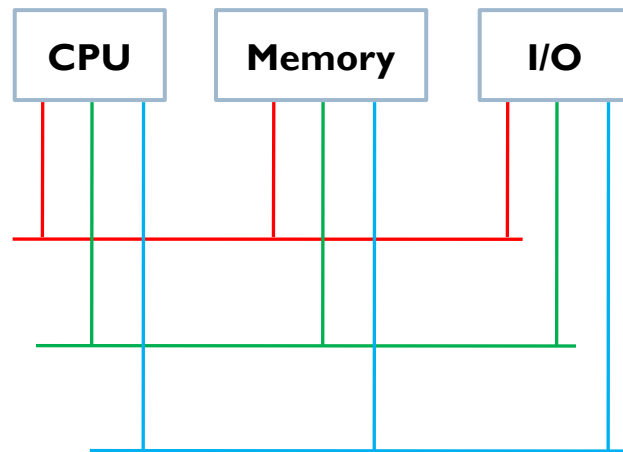
System bus



▶ **System bus**

- ▶ Connects the main components of the computer
- ▶ It represents the union of three buses:
 - ▶ Control
 - ▶ Addresses
 - ▶ Data

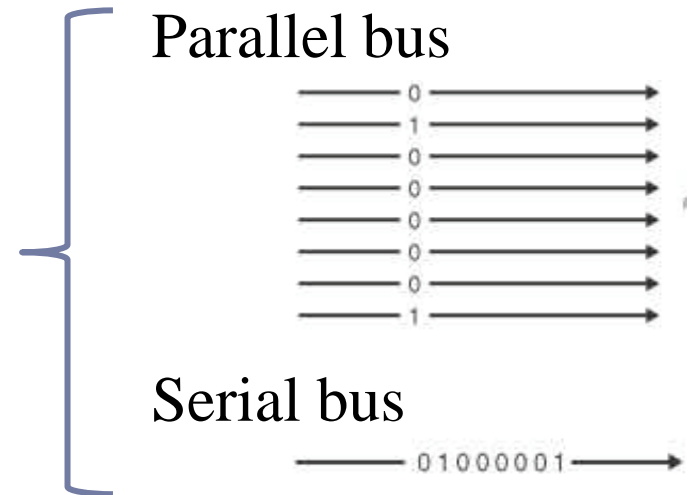
Buses



- ▶ **Data** bus
 - ▶ Transmits data
 - ▶ Its width and speed have a great influence on the performance
- ▶ **Address** bus
 - ▶ Memory addresses and I/O devices
 - ▶ Its width determines the maximum memory capacity
- ▶ **Control** bus
 - ▶ Control and timing signals

Characteristics of a bus

- ▶ **Bus width**: determines the number of bits that can be transmitted simultaneously



- ▶ **Frequency**: clock frequency with which it can operate
- ▶ **Transfer rate**: number of bytes per clock cycle
- ▶ **Bandwidth** (transfer rate): transmitted bytes per second
 - ▶ Transfer rate X frequency

Exercise

- ▶ Calculate the bandwidth in MBps of a 32-bit bus with a frequency of 66 MHz

Exercise (solution)

- ▶ Calculate the bandwidth in MBps of a 32-bit bus with a frequency of 66 MHz

$$\text{Bandwidth} = \frac{32 \text{ bits} \times 66 \text{ MHz}}{8 \text{ bits per byte}} = \frac{32 \times 66 \cdot 10^6}{8} = 264 \text{ MBps}$$

Arbitration method (bus protocol)

- ▶ Determines which of the elements connected to the bus can access the bus
- ▶ **Centralized** scheme: a bus controller grants the use of the bus
 - ▶ When an element wants to access the bus, it requests permission from the controller through the control lines (BUSRQ)
 - ▶ When the bus is free the controller grants the use (BUSACK)
- ▶ **Distributed** scheme: each element connected to the bus includes an access control logic that allows the joint use of the bus (access protocol)

Synchronous and asynchronous buses

- ▶ A **synchronous** bus is governed by a clock signal and a communication protocol set to the operation of the clock
 - ▶ Fast
 - ▶ All devices connected to it must operate at the same clock frequency
- ▶ An **asynchronous** bus does not use a clock, the communication is done by sending orders through the control lines of the bus

Bus hierarchies

- ▶ Problem:

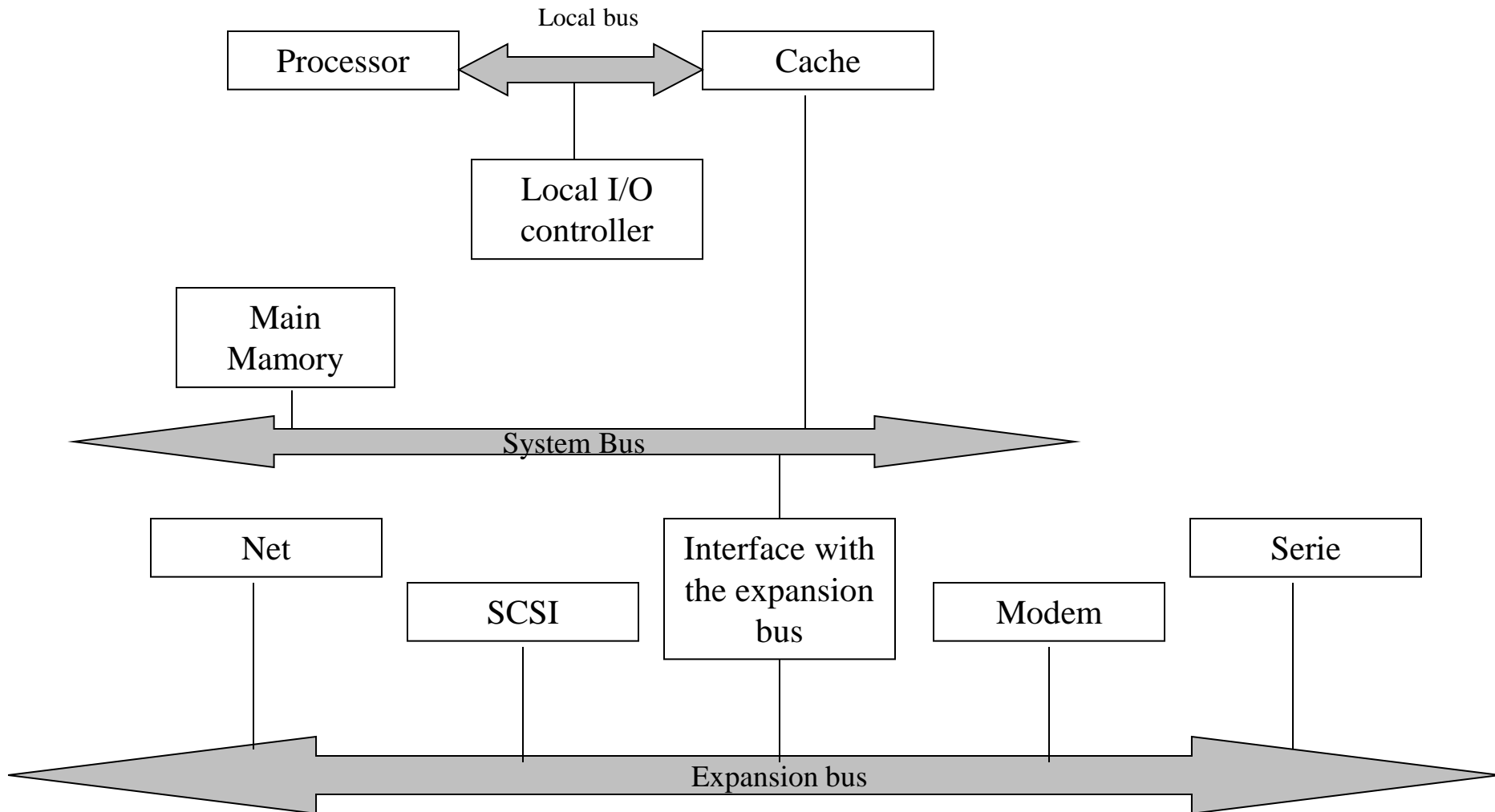
- ▶ The more devices connected to the bus, the longer the propagation delay.
- ▶ As the number of transfer requests increases, a bottleneck can occur.

- ▶ Solutions:

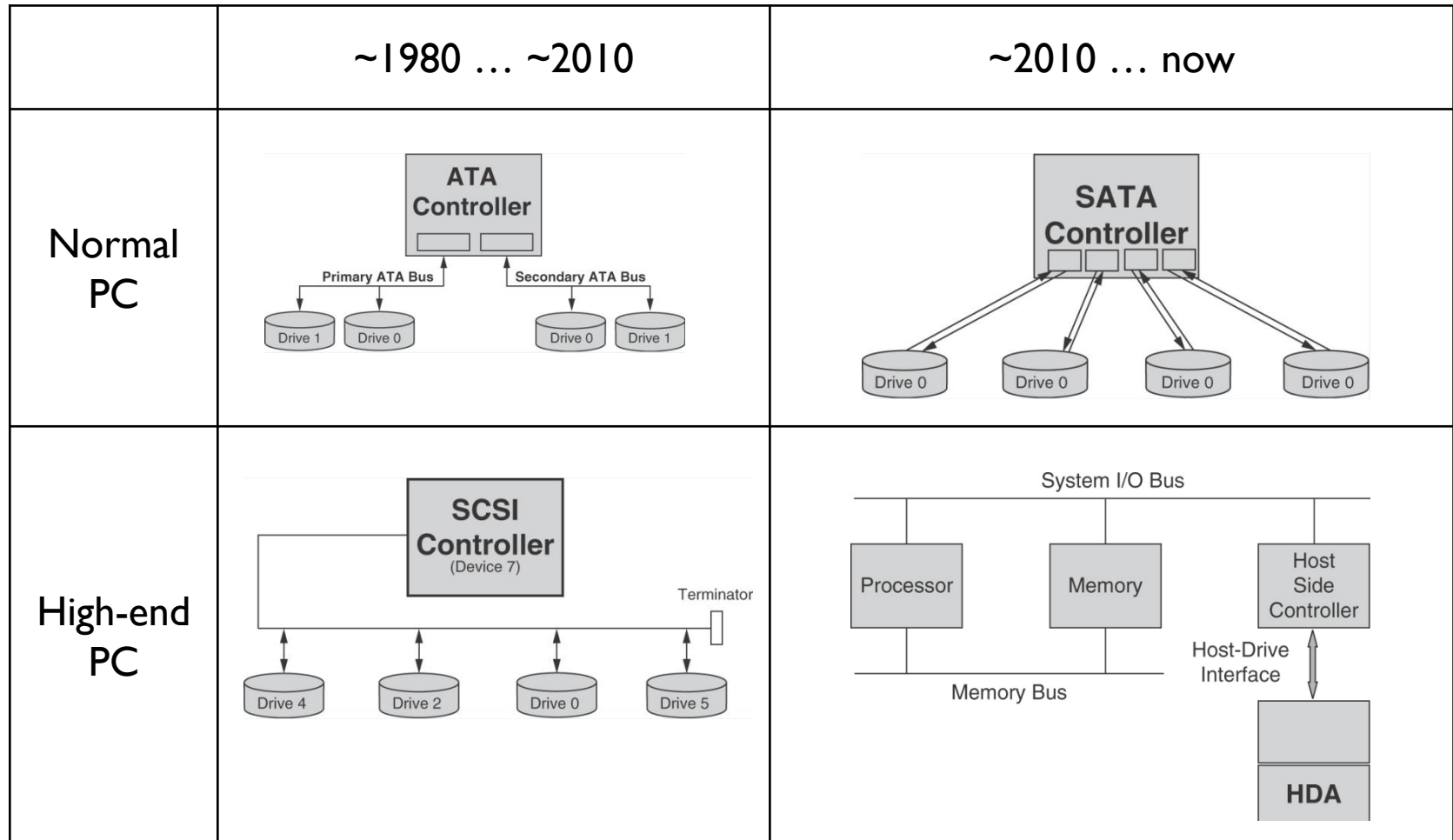
- ▶ Increase data transmission speed with wider buses.
- ▶ Use more data buses, organized hierarchically.

Bus hierarchies

Bus diagram in a typical computer system



Disks Controllers



Curiosity:

USB family



	Transfer (per sec.)	Introduction
USB4	40 Gbps	2019
USB 3.2	20 Gbps	2017
USB 3.0	600 MB/s	2010
USB 2.0	60 MB/s	2000
USB 1.0	1.5 MB/s and 187 KB/s	1996

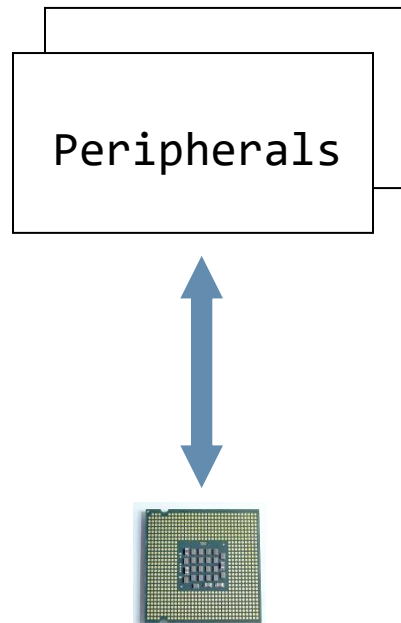
	Song / Pic	256 Flash	USB Flash	SD-Movie	USB Flash	HD-Movie
	4 MB	256 MB	1 GB	6 GB	16 GB	25 GB
USB 1.0	5.3 sec	5.7 min	22 min	2.2 hr	5.9 hr	9.3 hr
USB 2.0	0.1 sec	8.5 sec	33 sec	3.3 min	8.9 min	13.9 min
USB 3.0	0.01 sec	0.8 sec	3.3 sec	20 sec	53.3 sec	70 sec

<http://www.unp.co.in/f140/comparison-of-usb-3-0-port-with-usb-2-0-and-usb-1-0-a-70063/>

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Peripheral concept



- ▶ **Peripheral:**
 - ▶ Any external device that connects to a processor through the **input/output (I/O) modules**.
 - ▶ They allow storing information or communicating the computer with the outside world.

Classification of peripherals (by use)



► **Communication:**

► **Human-computer**

- (Terminal) keyboard, mouse, ...
- (Printer) plotter, scanner, ...

► **Computer-computer**

- Modem, network adapter

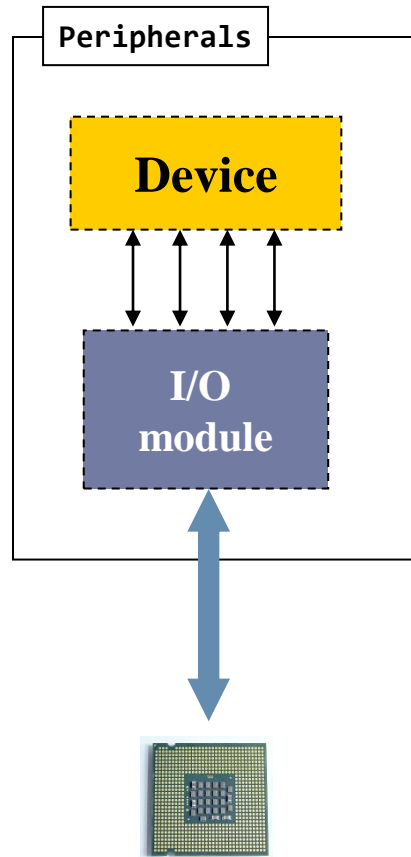
► **Physical environment**

- (read/action) x
(analogical/digital)

► **Storing:**

- Direct access (disks, DVD, ...)
- Sequential access (tapes)

General structure of a peripheral



- ▶ Consisting of:

- ▶ **Device**

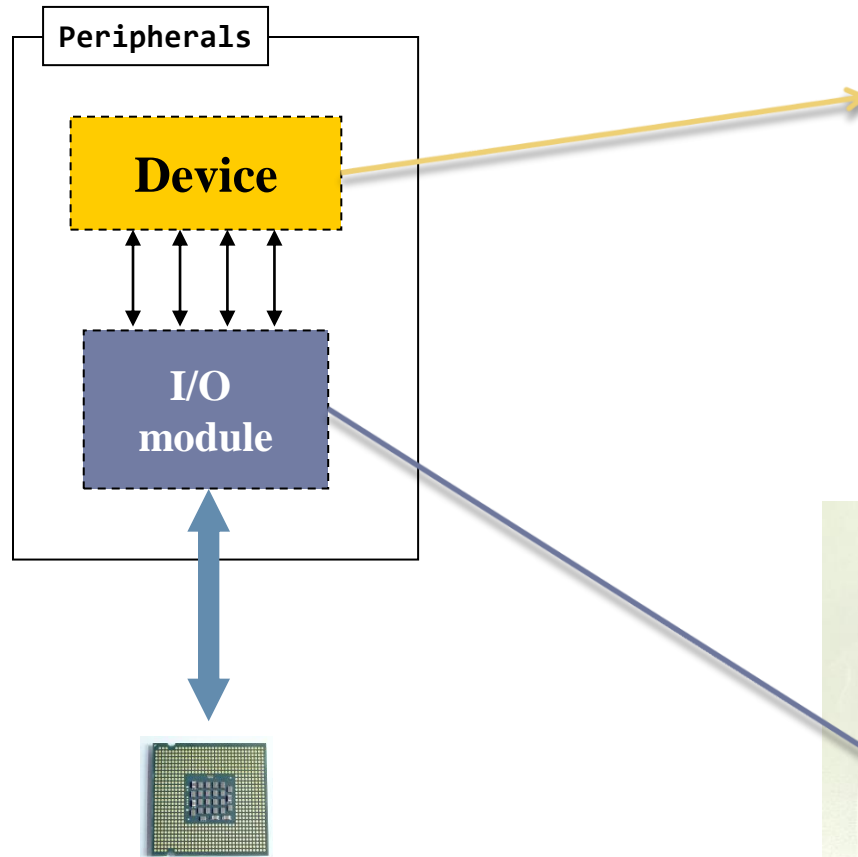
- ▶ Hardware that interacts with the environment

- ▶ **I/O module**

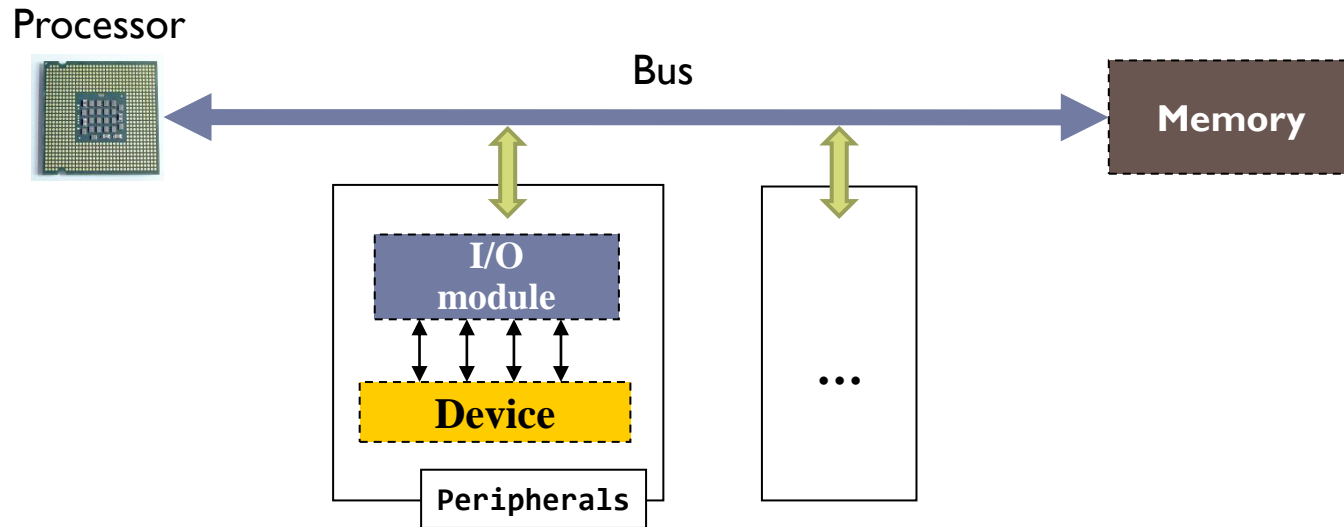
- ▶ Also called **controller** or **I/O unit**
 - ▶ Interface between the device and the processor, which hides the particularities of the processor.

Example:

Disk drive

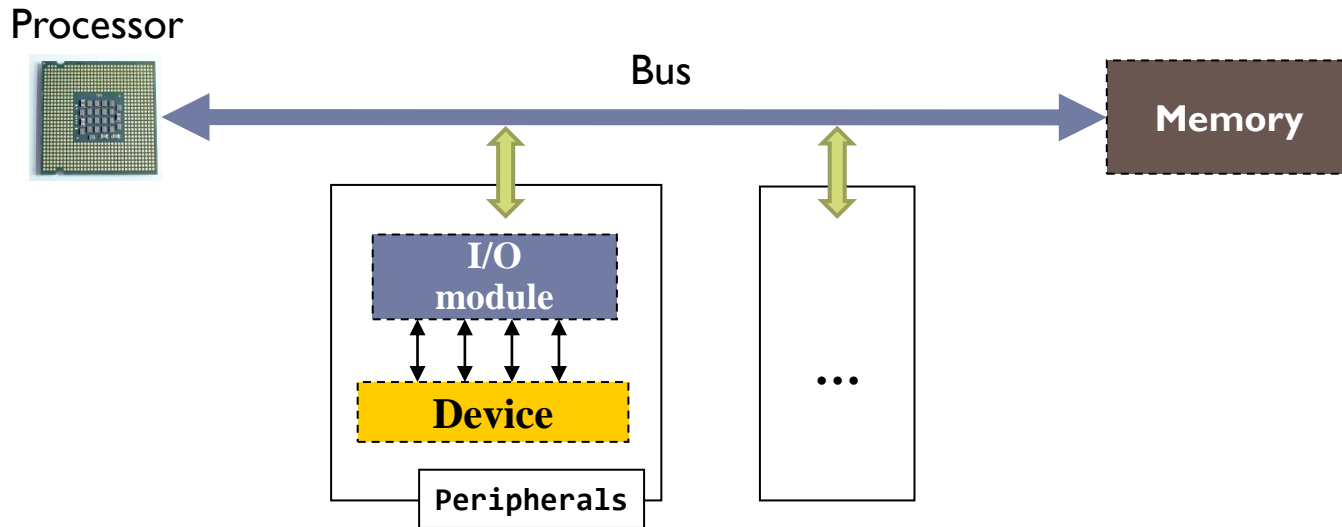


I/O module



- ▶ **I/O modules** perform the connection among the peripheral devices and the processor (or the memory)

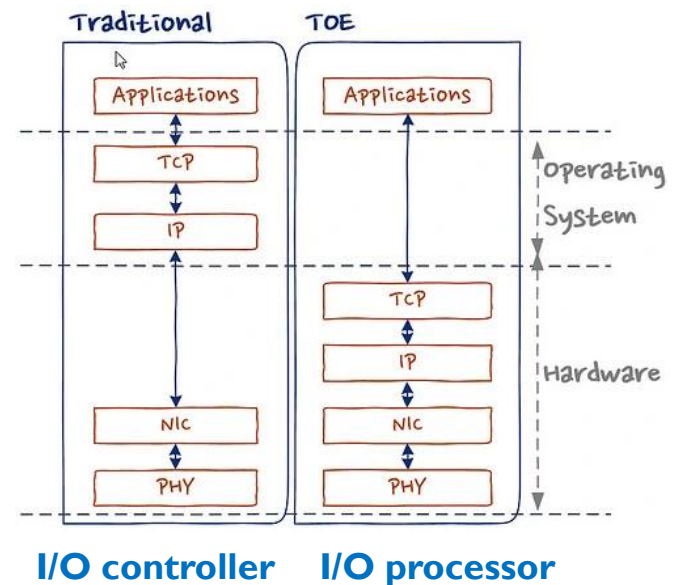
I/O module: why there are necessary?



- ▶ Wide variety of peripherals.
 - ▶ **Peripherals are 'peculiar'.**
- ▶ Data transfer rate of peripherals is much slower than memory or CPU ones.
 - ▶ **Peripherals are 'very slow'.**
- ▶ Formats and word sizes of peripherals different from those of the computer to which they are connected.

I/O module: range of possible tasks

- ▶ I/O module common tasks:
 - ▶ Control and timing
 - ▶ Error detection
 - ▶ Processor/device communication
 - ▶ Data buffering
 - ▶ Etc.
- ▶ I/O module types by complexity:
 - ▶ **I/O controller** or **device driver**: simpler module, which requires the CPU to have detailed control of the device.
 - ▶ **Channel I/O** or **I/O processor**: handles most of the processing details.



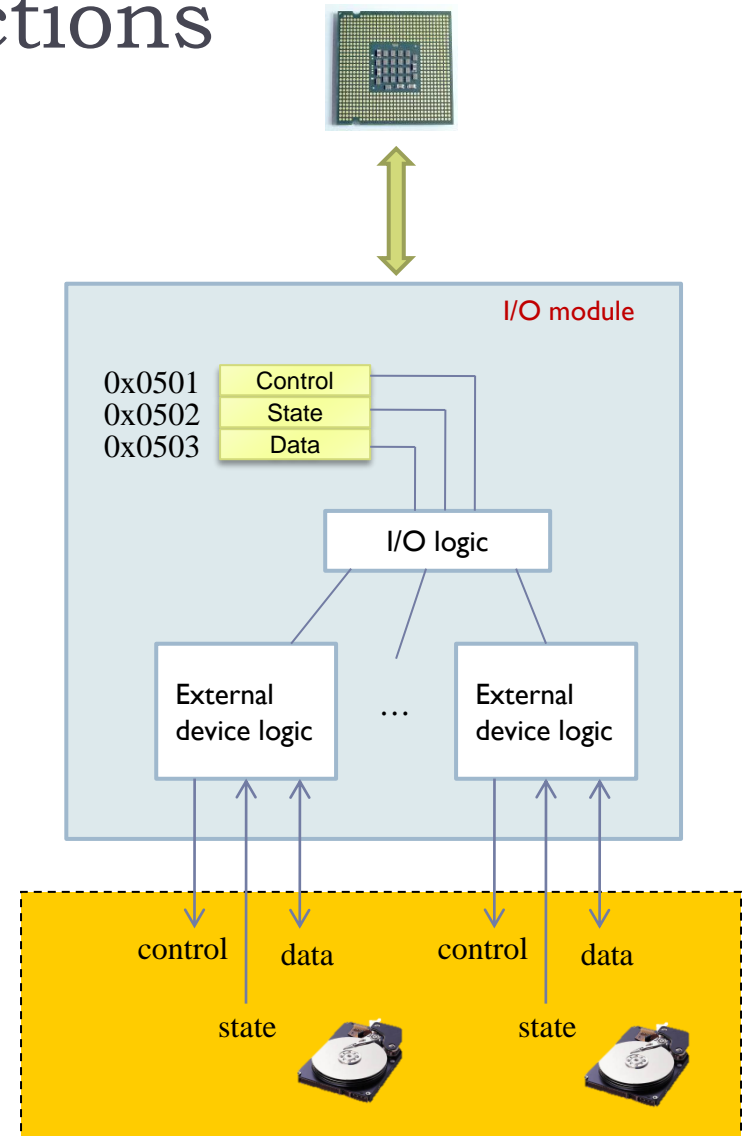
I/O module: main functions

▶ Attending to the CPU:

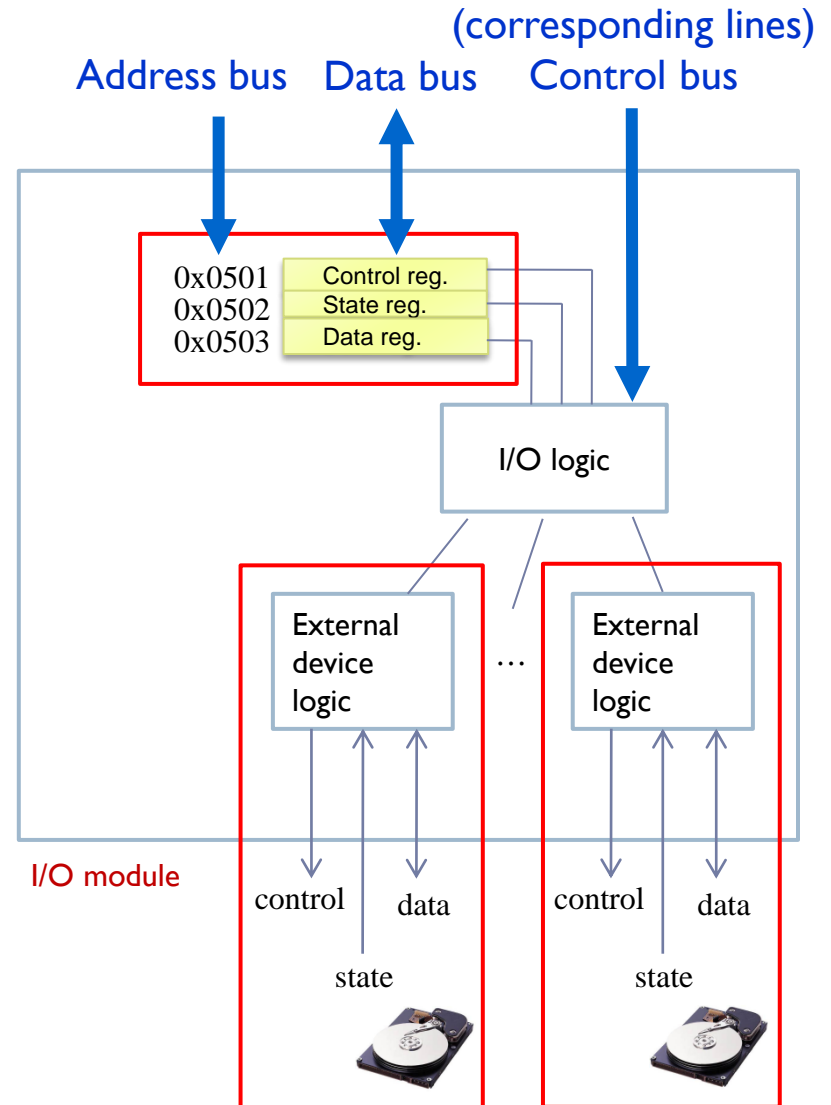
- ▶ Order decoding
- ▶ Status information
- ▶ Control and timing
 - ▶ E.g.: data to M.M.

▶ Control peripheral(s):

- ▶ Communication with peripherals
- ▶ Error detection
- ▶ Temporary data storage
 - ▶ peripheral->processor

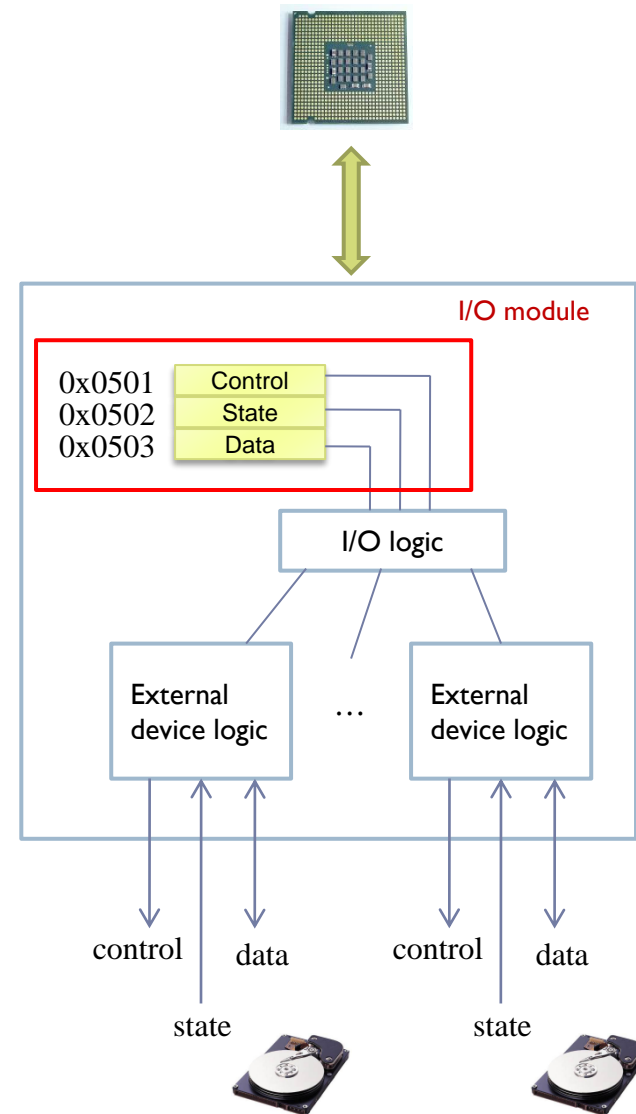


Simplified I/O module model



Simplified I/O module model

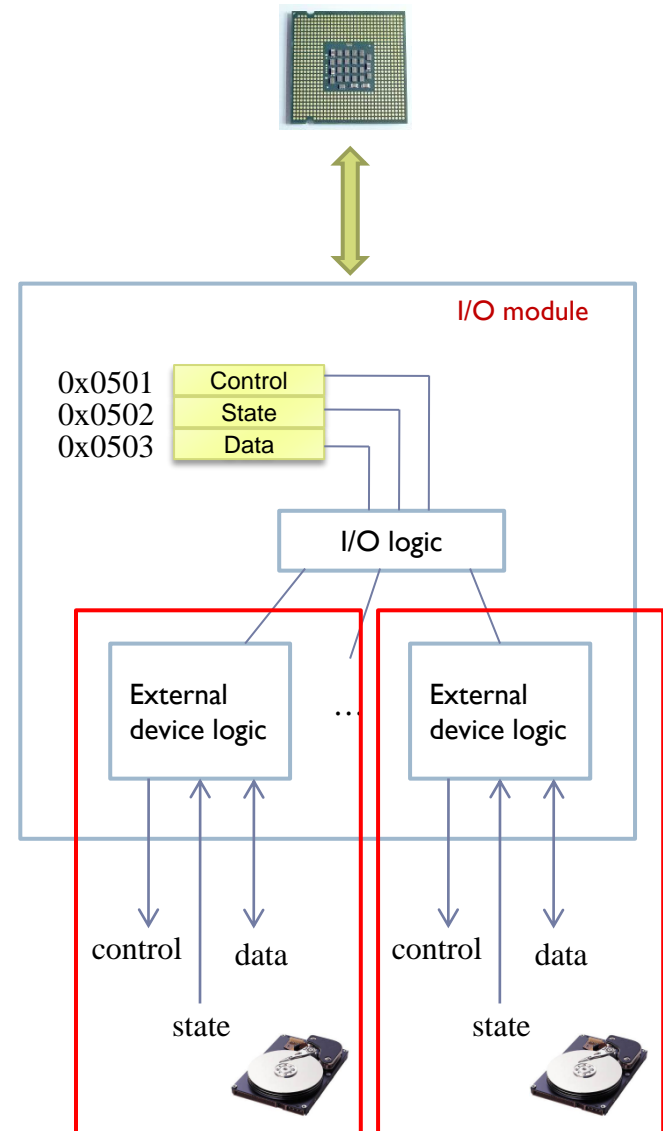
- ▶ Interaction between processor and I/O module through 3 registers:
 - ▶ The **control** register
 - ▶ Commands for the peripheral
 - ▶ The **state** register
 - ▶ Status of the last command
 - ▶ The **data** register
 - ▶ Data exchanged processor/peripheral



Simplified I/O module model

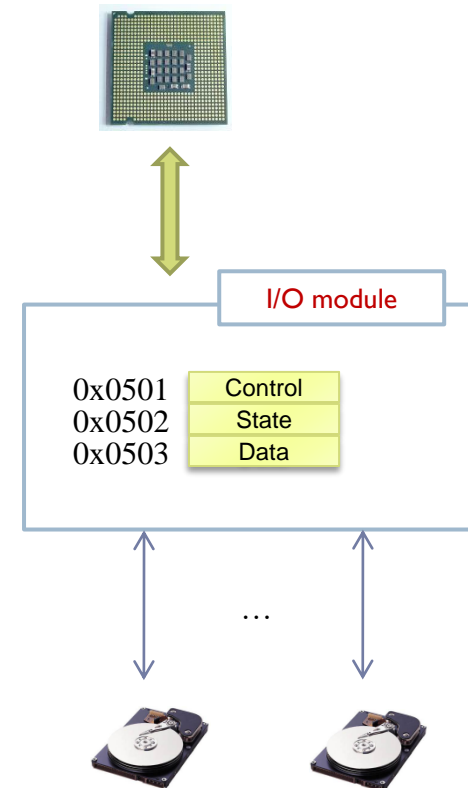
- ▶ Interaction between peripheral and I/O module:

- ▶ **Data signals (lines):**
for transferring information
- ▶ **State signals (lines):**
information about the device
 - ▶ Examples:
 - New data available
 - Peripheral on/off
 - Peripheral busy
 - Peripheral up and running
 - Error in last command
 - ...
- ▶ **Control signals (lines):**
to control the peripheral/device
 - ▶ Examples:
 - Power on/off
 - Skip page in a printer
 - Seek in a hard disk
 - ...



I/O module: main characteristics

- ▶ **Transfer unit**
 - ▶ Block
 - ▶ Character
- ▶ **Addressing**
 - ▶ Memory-mapped I/O
 - ▶ Port-mapped I/O
- ▶ **I/O techniques**
 - ▶ Programmed I/O
 - ▶ Interrupt I/O
 - ▶ DMA



Characteristics (1/3):

Transfer unit

- ▶ **Transfer unit**
 - ▶ Block
 - ▶ Character
- ▶ **Addressing**
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▶ **Block devices:**

- ▶ Unit: **block** of bytes
- ▶ Access: **sequential** or **random**
- ▶ Operations: read, write, seek, ...
- ▶ Examples: “tapes” and disks



▶ **Character devices:**

- ▶ Unit: **chars** (ASCII, Unicode, etc.)
- ▶ Access: **sequential** to characters
- ▶ Operations : get, put,
- ▶ Example: terminals, printers, etc.



Characteristics (2/3):

I/O addressing

▶ **Memory-mapped I/O (MMIO)**

- ▶ I/O registers are mapped in memory using a set of memory addresses for these registers.
- ▶ Same machine instructions for memory and I/O:

- `lw $a0, label2_disk1`

- Load in the processor register “\$a0” the value stored in the I/O register identified by a given address “label2_disk1”

- `sw $a0, label_disk2`

- To write an item in an I/O register from the I/O module

▶ **Port-mapped I/O (PMIO):**

- ▶ I/O address space is isolated from memory address space.

- ▶ Special privileged machine instructions (~ to lw/sw):

- `IN $a0, label2_disk1`

- Load in the processor register “\$a0” the value stored in the I/O register identified by a given address “label2_disk1”

- `OUT $a0, label_disk2`

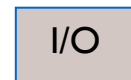
- To write an item in an I/O register from the I/O module

- ▶ **Transfer unit**
 - ▶ Block
 - ▶ Character
- ▶ **Addressing**
 - ▶ Memory-mapped I/O
 - ▶ Port-mapped I/O
- ▶ **I/O techniques**
 - ▶ Programmed I/O
 - ▶ Interrupt I/O
 - ▶ DMA

`lw Reg., add.`
`sw Reg., add.`



`in Reg., add.`
`out Reg., add.`



`lw Reg., add.`
`sw Reg., add.`



Linux

```

phenix.arcos.inf.uc3m.es - default* - SSH Secure Shell
File Edit View Window Help
acaldero@phenix:~$ cat /proc/ioports
0000-0cf7 : PCI Bus 0000:00
0000-001f : dma1
0020-0021 : pic1
0040-0043 : timer0
0050-0053 : timer1
0060-0060 : keyboard
0064-0064 : keyboard
0070-0073 : rtc0
0080-008f : dma page reg
00a0-00a1 : pic2
00c0-00df : dma2
00f0-00ff : fpu
0290-029f : pnp 00:01
0290-0294 : pnp 00:01
02f8-02ff : serial
0378-037a : parport0
03c0-03df : vga+
03f2-03f2 : floppy
03f4-03f5 : floppy
03f7-03f7 : floppy
03f8-03ff : serial
0400-047f : 0000:00:1f.0
0400-0403 : ACPI PM1a_EVT_BLK
0404-0405 : ACPI PM1a_CNT_BLK
Connected to phoenix.arcos.inf.uc3m.es

```

Windows

Información del sistema

Archivo Editar Ver Ayuda

Resumen del sistema	Recurso	Dispositivo
Recursos de hardware	0x00000000-0x0000000F	Controladora de acceso directo a r
Conflictos/uso compartido	0x00000000-0x0000000F	Bus PCI
DMA	0x00000010-0x0000001F	Recursos de la placa base
Hardware forzado	0x00000020-0x000000...	Controladora programable de inte
E/S	0x00000022-0x0000003F	Recursos de la placa base
IRQs	0x00000040-0x000000...	Cronómetro del sistema
Memoria	0x00000044-0x0000005F	Recursos de la placa base
Componentes	0x00000060-0x000000...	Recursos de la placa base
Entorno de software	0x00000061-0x000000...	Altavoz del sistema
	0x00000062-0x000000...	Recursos de la placa base
	0x00000064-0x000000...	Recursos de la placa base
	0x00000065-0x0000006F	Recursos de la placa base
	0x00000070-0x000000...	Sistema CMOS/reloj en tiempo real
	0x00000072-0x0000007F	Recursos de la placa base
	0x00000080-0x000000...	Recursos de la placa base
	0x00000081-0x000000...	Controladora de acceso directo a r
	0x00000084-0x000000...	Recursos de la placa base
	0x00000087-0x000000...	Controladora de acceso directo a r
	0x00000088-0x000000...	Recursos de la placa base
	0x00000089-0x000000...	Controladora de acceso directo a r
	0x0000008C-0x000000...	Recursos de la placa base

Buscar esto:

☐ Buscar sólo la categoría seleccionada ☐ Buscar sólo nombres de categoría

Characteristics (3/3): I/O techniques

- ▶ **Transfer unit**
 - ▶ Block
 - ▶ Character
- ▶ **Addressing**
 - ▶ Memory-mapped I/O
 - ▶ Port-mapped I/O
- ▶ **I/O techniques**
 - ▶ Programmed I/O
 - ▶ Interrupt I/O
 - ▶ DMA

- ▶ **I/O techniques:**
Processor and I/O_module interaction
 - ▶ **Programmed I/O**
 - ▶ **Interrupt I/O**
 - ▶ **DMA(Direct Memory Access) I/O**

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ARCOS @ UC3M
Félix García Carballera, Alejandro Calderón Mateos

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A little bit of history...



- ▶ First hard disk introduced in 1956
 - ▶ It was called IBM RAMAC 305
 - ▶ 50 aluminum disks of 61 cm (24") diameter
 - ▶ 5 MB of data
 - ▶ Spun at 3,600 revolutions per minute (RPM)
 - ▶ Had a transfer speed of 8.8 Kbps
 - ▶ 35 000\$ per year rental
 - ▶ Weighed about one ton

1956

1980

1999

A little bit of history...



Sept 13, 1956 - IBM, today unveiled its new Ramac 305 super computer to the anxiously awaiting business, governmental and military world. The machine, with the first disk drive storage in the industry, is capable of handling electronic data faster and in greater quantities than any prior computer of its size. Seen here at the San Jose, Notre Dame Development Lab, demonstrating its capabilities for the press, is IBM employee, Wanda Little.

- ▶ IBM RAMAC 305 (1956)
 - ▶ 50 aluminum disks of 61 cm (24") diameter
 - ▶ 5 MB of data
 - ▶ 3,600 RPM
 - ▶ transfer speed: 8.8 Kbps
 - ▶ 35 000\$ per year rental

1956

1980

1999

A little bit of history...

- ▶ In 1980 appeared the first 5 1/4" disk
 - ▶ 5 MB
 - ▶ ~4 500 \$



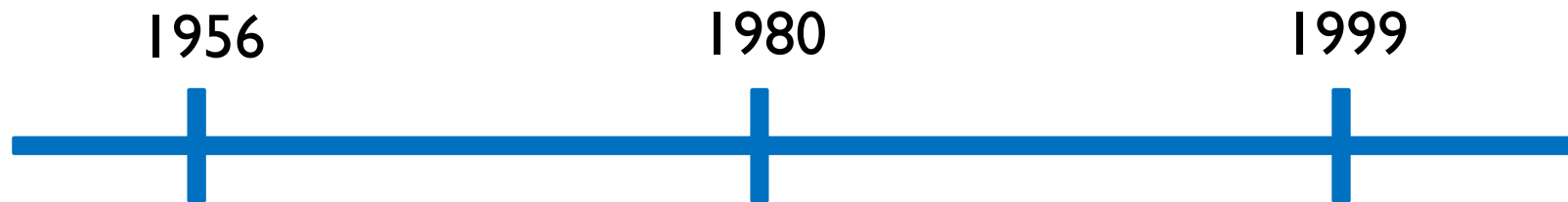
1956

1980

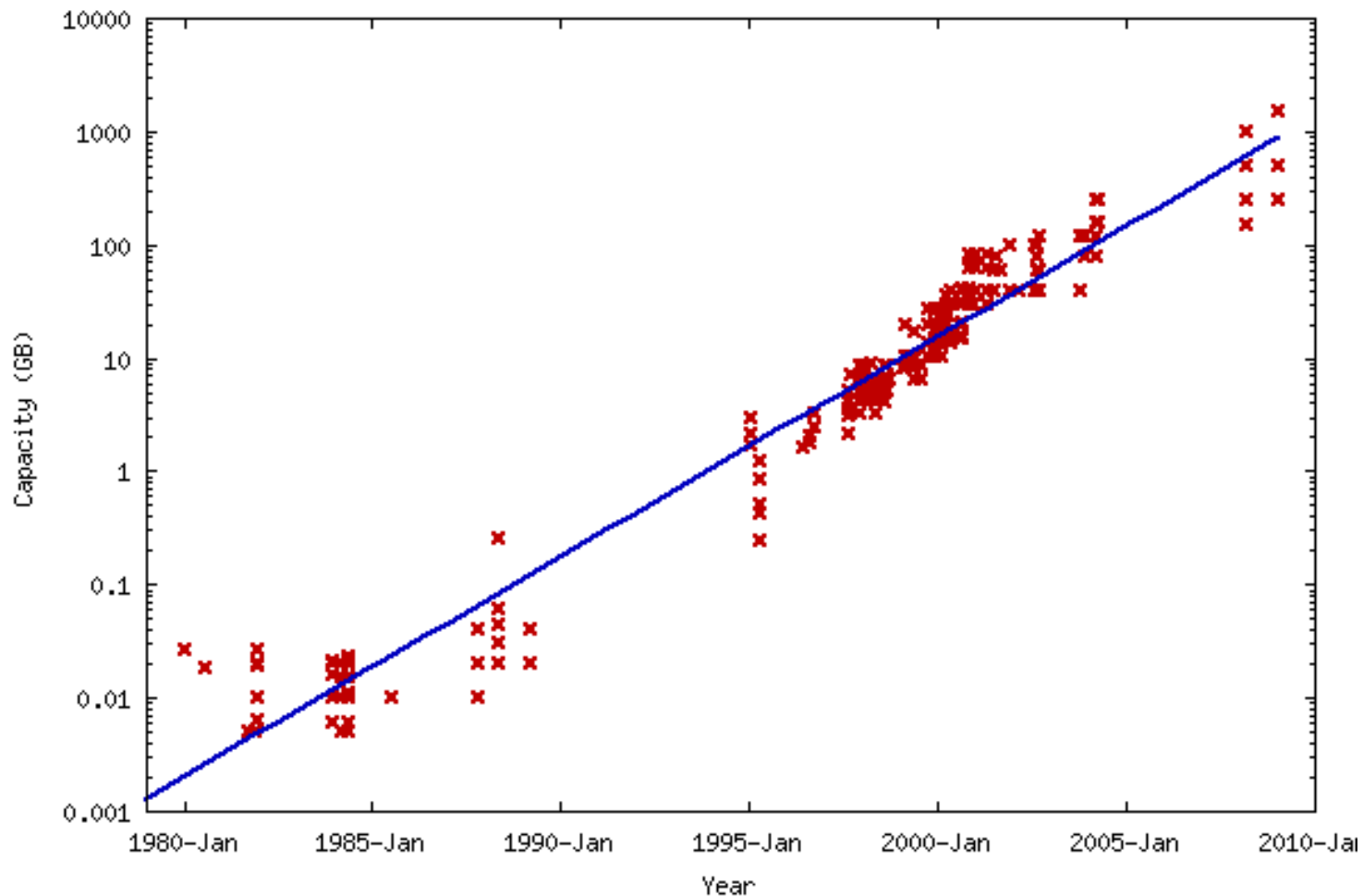
1999

A little bit of history...

- ▶ In 1997 appeared the first disk with 15 000 RPM
- ▶ In 1999 is introduced the Microdrive
 - ▶ IBM+Hitachi, 170 MiB
 - ▶ The 2005 microdrive reach 6 GiB



Evolution...



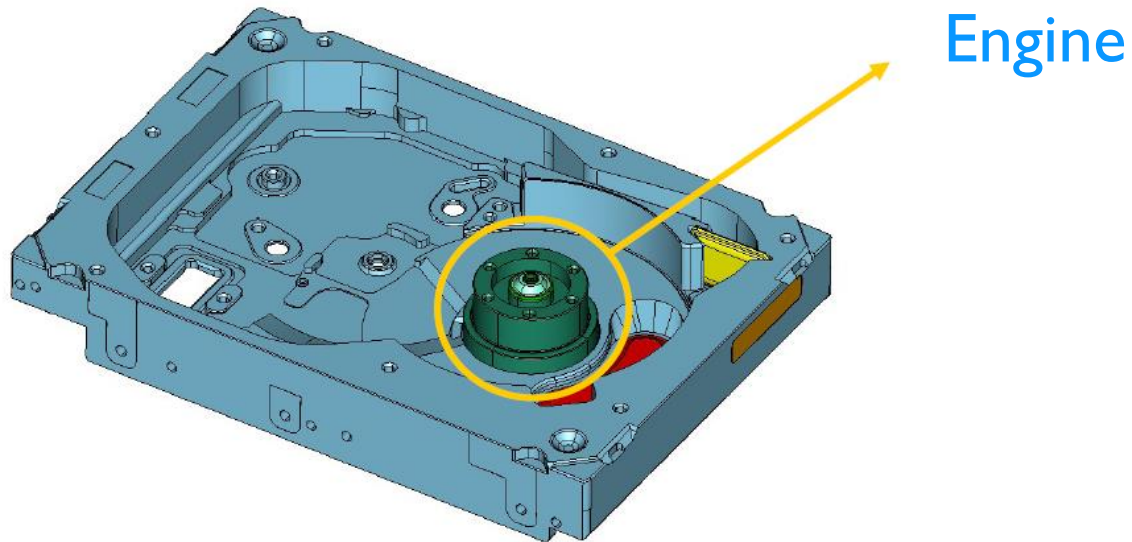
Evolution...

	Annual growth rate
Capacity	1.93 / year
Cost	0.60 / year
Performance	0.05 / year



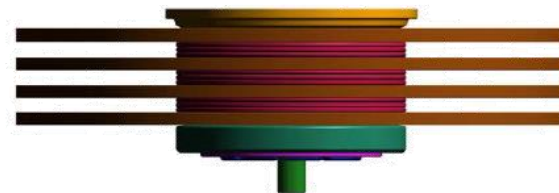
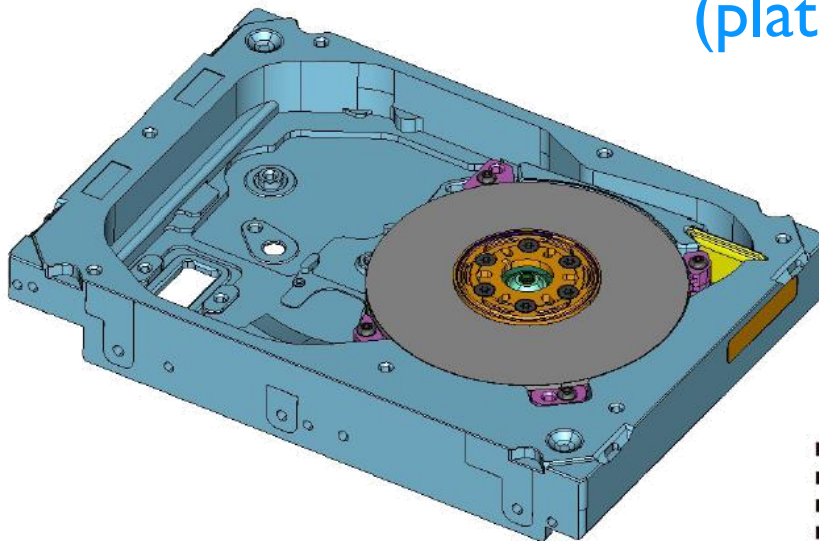
<https://www.pingdom.com/blog/amazing-facts-and-figures-about-the-evolution-of-hard-disk-drives/>

Anatomy of a hard disk drive



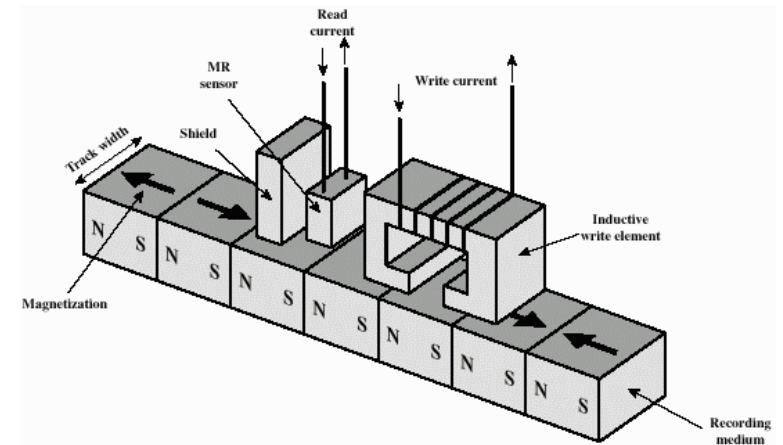
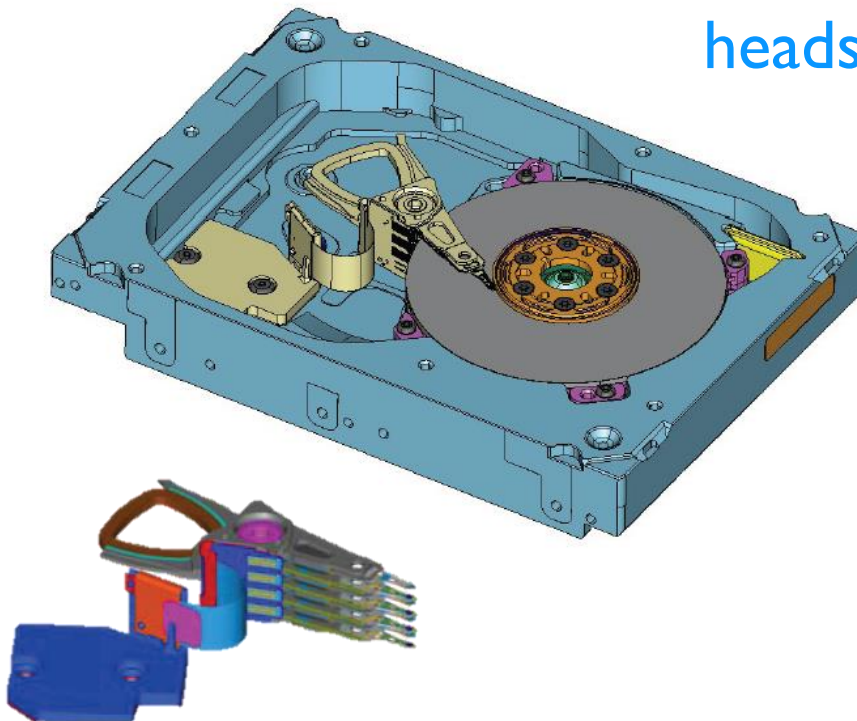
Anatomy of a hard disk drive

Disks
(plates)



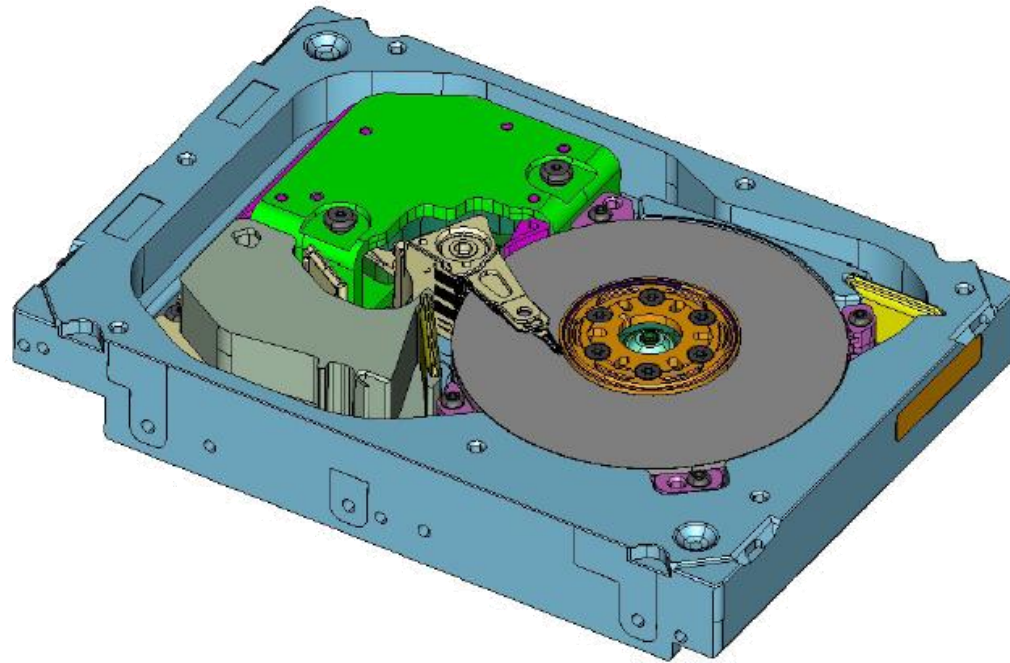
Anatomy of a hard disk drive

Read/write
heads



https://faculty.etsu.edu/TARNOFF/ntes2150/mem_hier/mem_hier.html

Anatomy of a hard disk drive



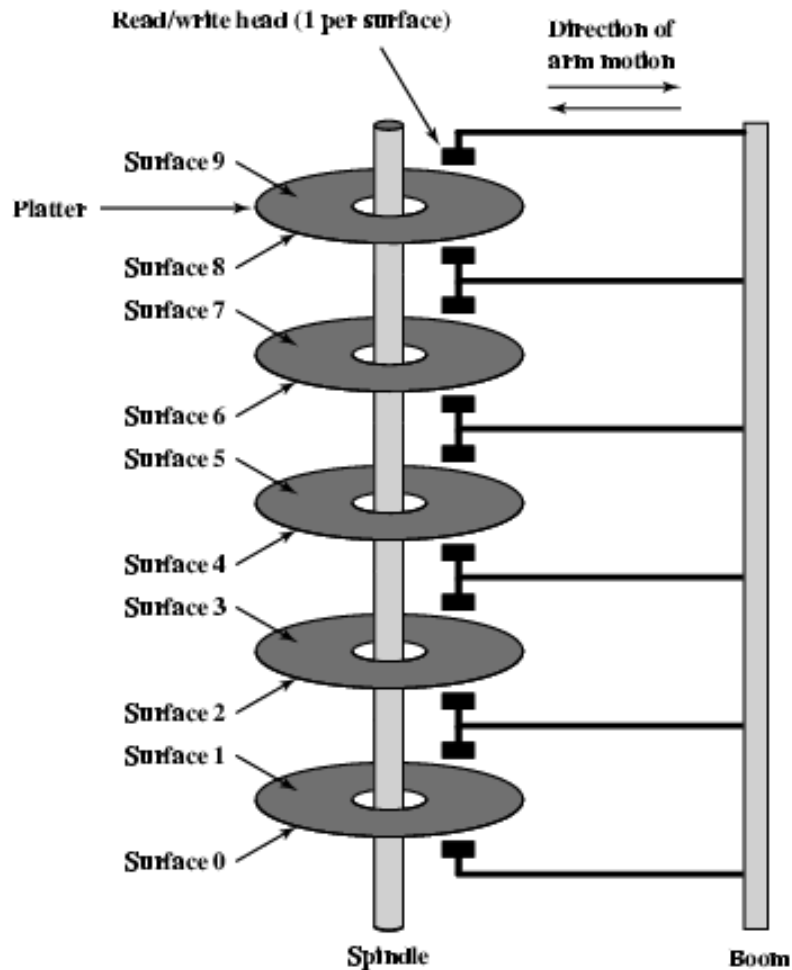
control and
mechanic module

Anatomy of a hard disk drive

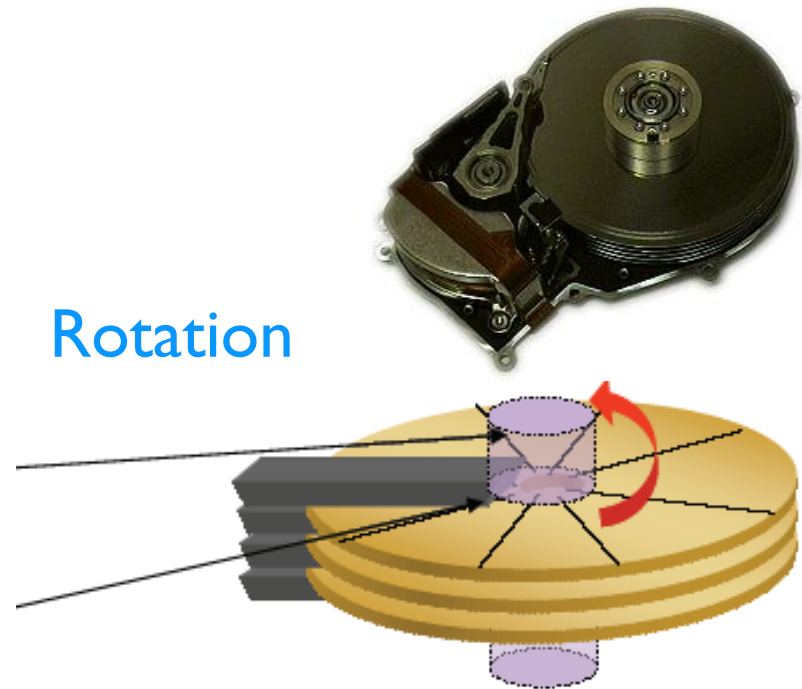


- ▶ **Disk controller**
 - ▶ Command scheduling
 - ▶ Error correction
 - ▶ Optimization
 - ▶ Integrity check
 - ▶ Revolutions per minute (RPM) monitoring
 - ▶ Disk cache

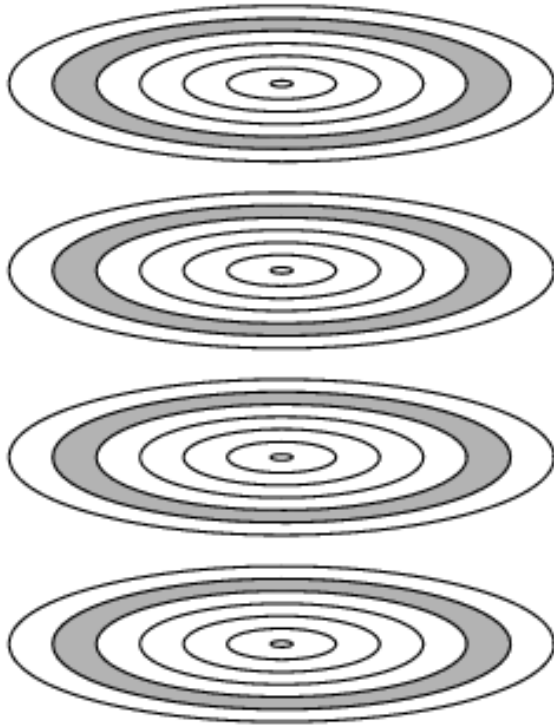
Multiple plates



<http://www.snia.org>

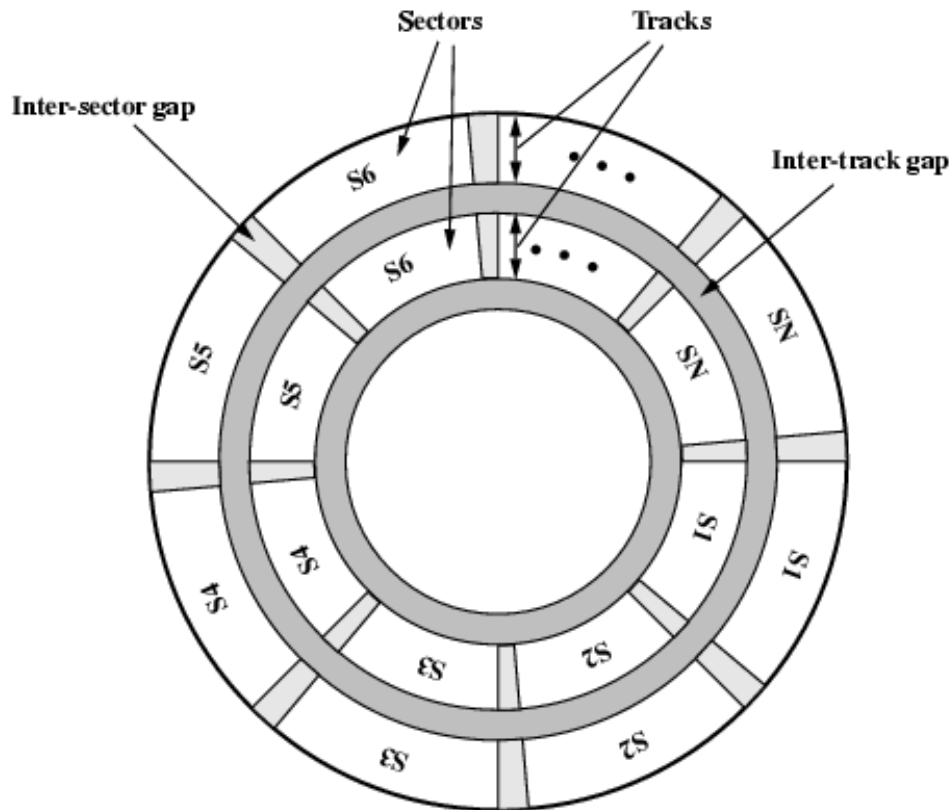


Cylinders



- **Cylinder:**
information accessed by
all heads in a rotation

Tracks, sectors and blocks



Track:

- ▶ Concentric ring in plate

Sector:

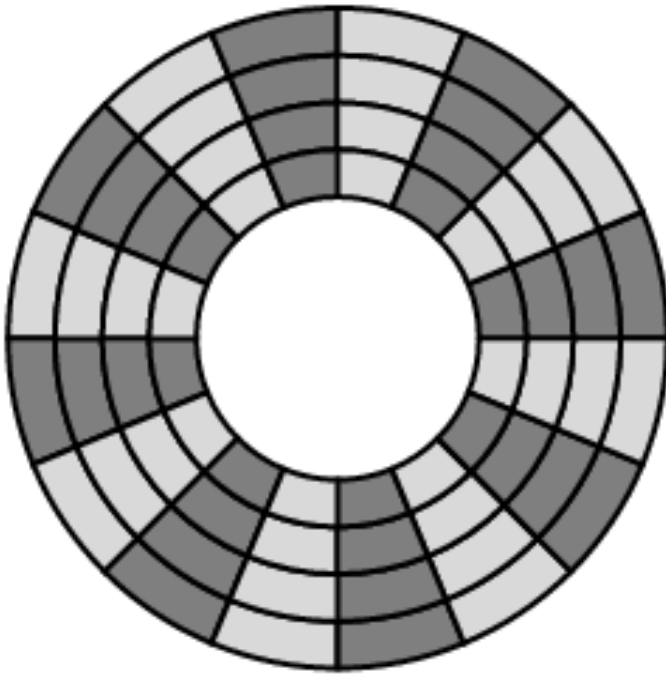
- ▶ Disk area division performed on formatting (typically 512 bytes)

Block:

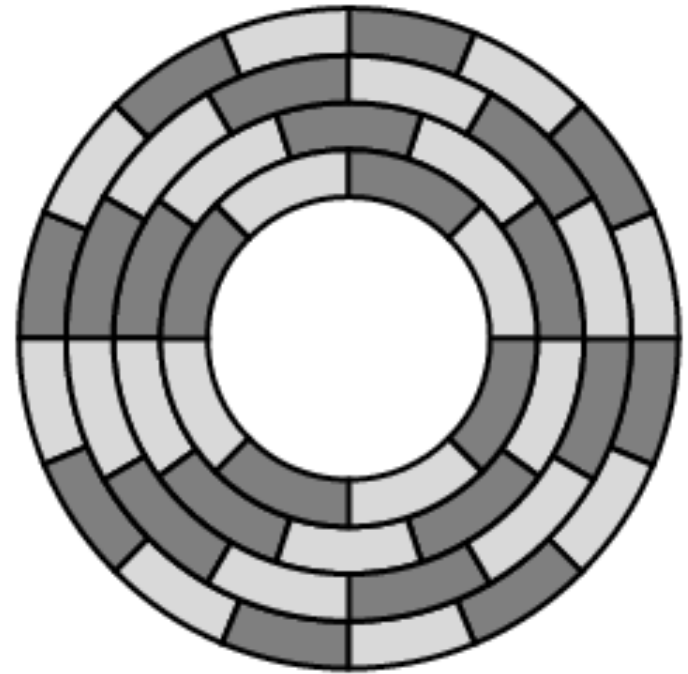
- ▶ File System writes in blocks
- ▶ Sector groups

Source: Stallings, William, Computer Organization & Architecture, 6e, Prentice Hall, Upper Saddle River, NJ, Figure 6.2, p. 166.

Distribution of sectors



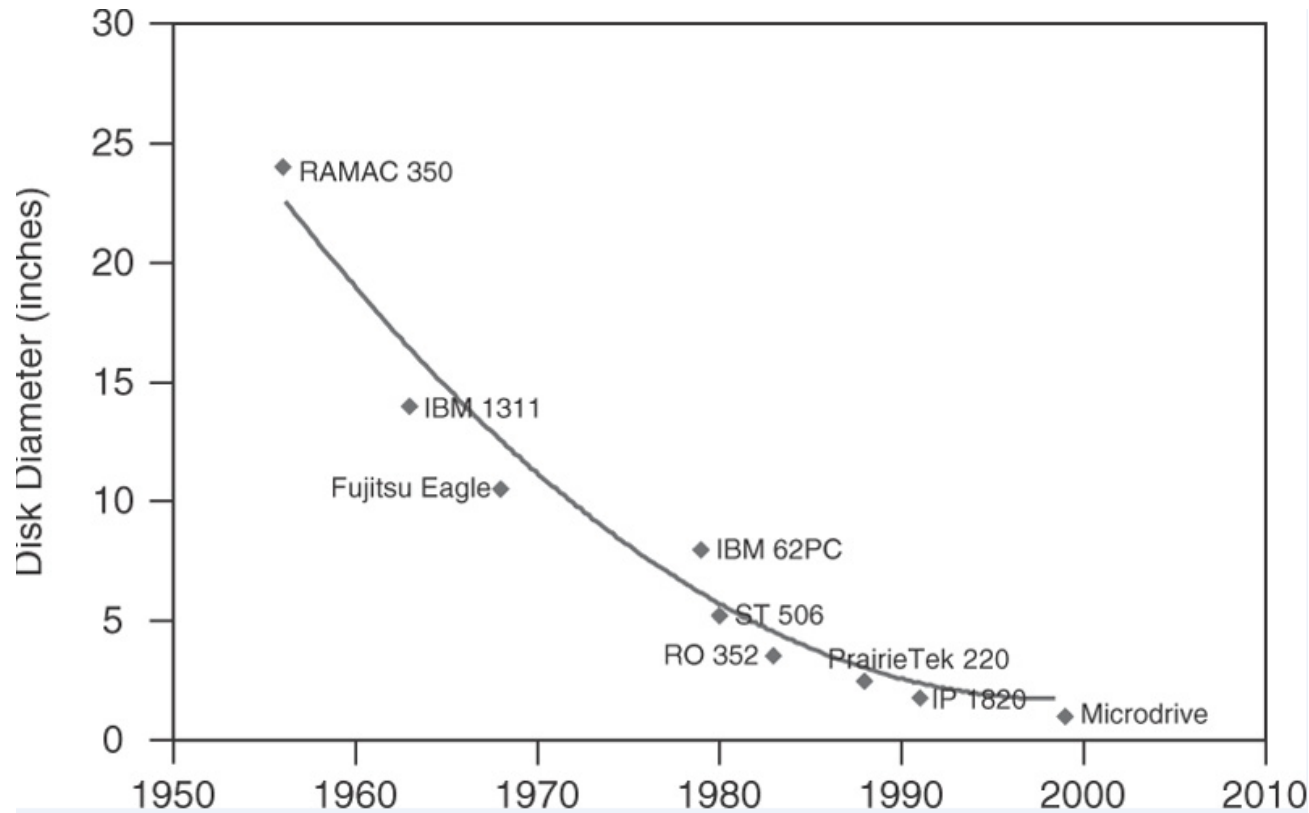
(a) Constant angular velocity



(b) Multiple zoned recording

Stallings, William, Computer Organization & Architecture, 6e, Prentice Hall, Upper Saddle River, NJ, Figure 6.3, p. 167.

Evolution of disk sizes



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Capacity

▶ Bits per inch

- ▶ They depend on the read/write head, the recording medium, the rotation of the disk and the speed at which the bus can accept data.

▶ Tracks per inch

- ▶ They depend on the read/write head, the recording medium, the precision with which the head can be positioned and the ability of the disk to rotate in a perfect circle.

Storage capacity

- ▶ For constant angular velocity disks:

- ▶ n_s : number of surfaces
- ▶ p : tracks per surfaces
- ▶ s : sectors per track
- ▶ t_s : bytes per sector

$$Capacity = n_s \times p \times s \times t_s$$

- ▶ For multiple zone recording:

- ▶ z : number of zones
- ▶ p_i : number of track per zone i
- ▶ s_i : sectors per track in zone i

$$Capacity = n_s \times t_s \times \sum_{i=1}^z (p_i \times s_i)$$

Exercise

- ▶ How many bytes does a disk drive of 250 GB store?

Remainder

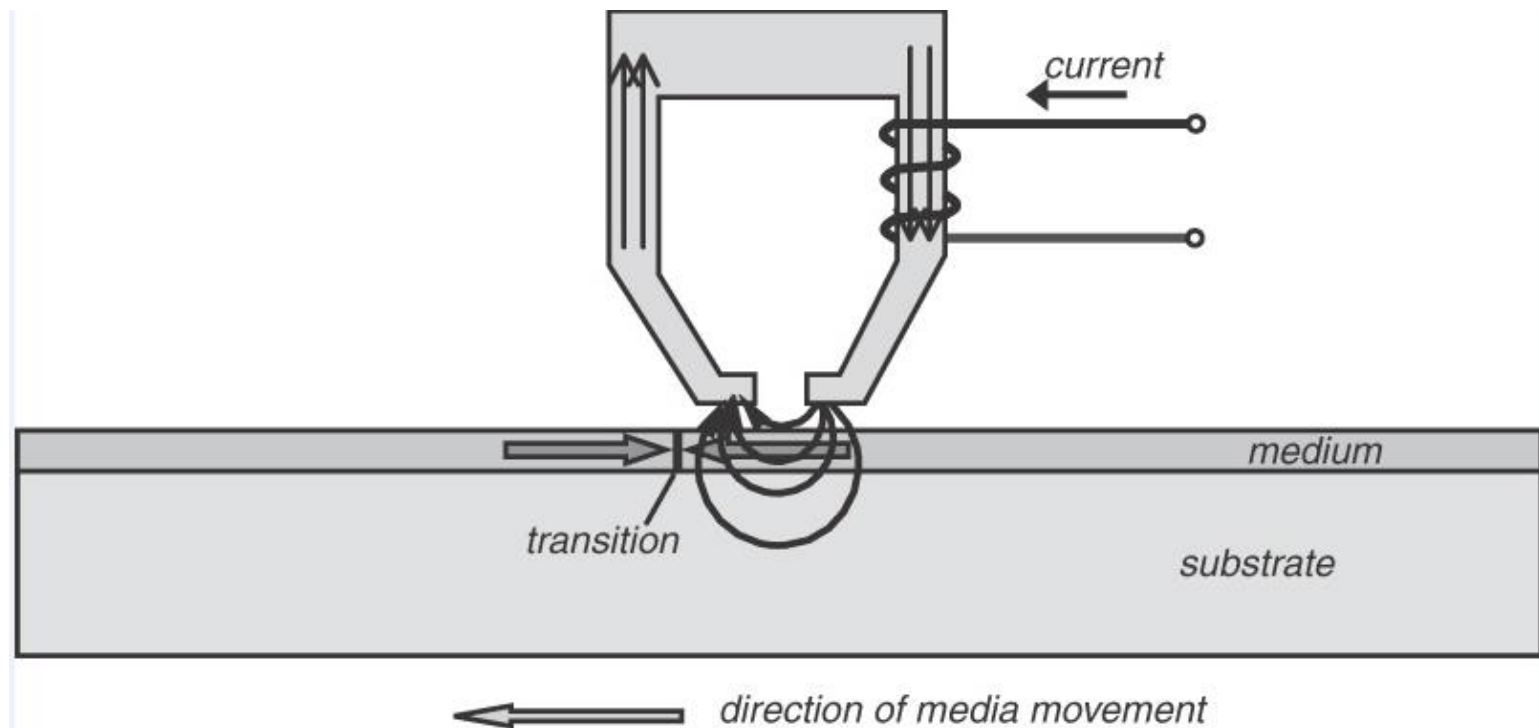
- ▶ 1 KB = 1024 bytes, but in the I.S. is 1000 bytes
- ▶ Manufactures of disk drives and telecommunications use I.S.:
 - ▶ A disk drive of 30 GB stores 30×10^9 bytes
 - ▶ A network of 1 Mbit/s transfers 10^6 bps.

Name	Abr	Factor	I.S.
Kilo	K	$2^{10} = 1,024$	$10^3 = 1,000$
Mega	M	$2^{20} = 1,048,576$	$10^6 = 1,000,000$
Giga	G	$2^{30} = 1,073,741,824$	$10^9 = 1,000,000,000$
Tera	T	$2^{40} = 1,099,511,627,776$	$10^{12} = 1,000,000,000,000$
Peta	P	$2^{50} = 1,125,899,906,842,624$	$10^{15} = 1,000,000,000,000,000$
Exa	E	$2^{60} = 1,152,921,504,606,846,976$	$10^{18} = 1,000,000,000,000,000,000$
Zetta	Z	$2^{70} = 1,180,591,620,717,411,303,424$	$10^{21} = 1,000,000,000,000,000,000,000$
Yotta	Y	$2^{80} = 1,208,925,819,614,629,174,706,176$	$10^{24} = 1,000,000,000,000,000,000,000,000$

Recording techniques

- ▶ Over the last decade the magnetic recording has achieved 100% growth of Areal Density (AD)
- ▶ Each bit cell in a track is composed of multiple magnetic grains
- ▶ The size or the number of magnetic grains in a bit cell cannot be scaled much below a diameter of ten nanometers due to:
 - ▶ Superparamagnetic effect
 - ▶ Ambient temperature would become magnetic grains unstable
- ▶ Recording techniques:
 - ▶ Longitudinal recording:
store data in a longitudinal way over a horizontal plane
 - ▶ Perpendicular recording:
data are stored in vertical way, increasing the disk capacity

Read/write head



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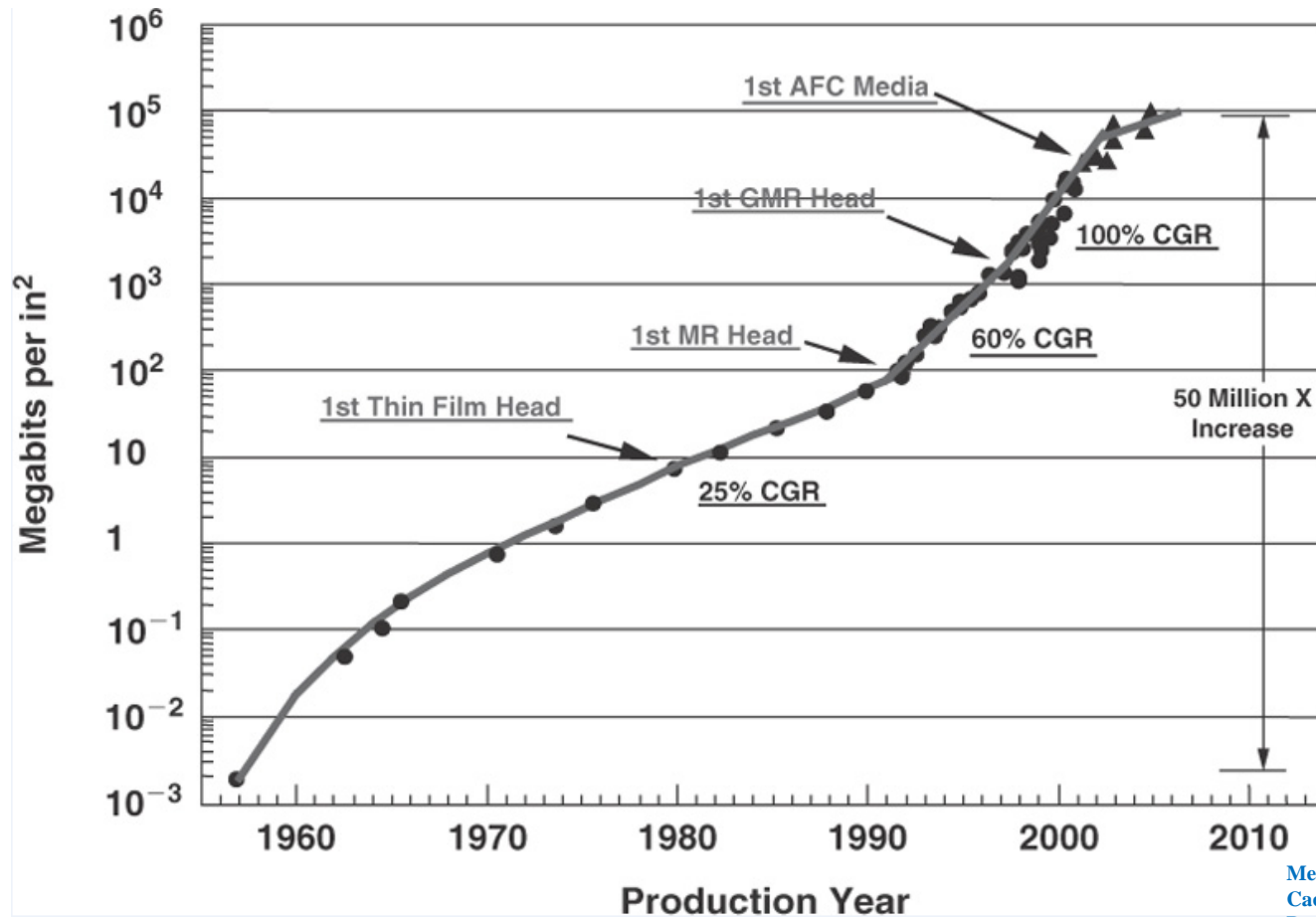
Areal density

- ▶ Improvements in disk capacity are expressed as an improvement in **areal density** (number of bits that can be recorded per square inch):

$$\text{Areal density (AD)} = \frac{\text{Tracks on a disk surface}}{\text{Inch}} \times \frac{\text{Bits on a track}}{\text{Inch}}$$

- ▶ Until 1998 the annual increase rate was 29%
- ▶ 1998-1997 the annual increase rate was 60%
- ▶ 1997-2003 the annual increase rate was 100%
- ▶ 2003-2011 the annual increase rate was 30%
- ▶ In 2011 the bigger areal density in commercial products was 400 billions of bits per square inch
- ▶ The cost per bit has improved in a factor of 1.000.000 between 1983 and 2011

Evolution of areal density

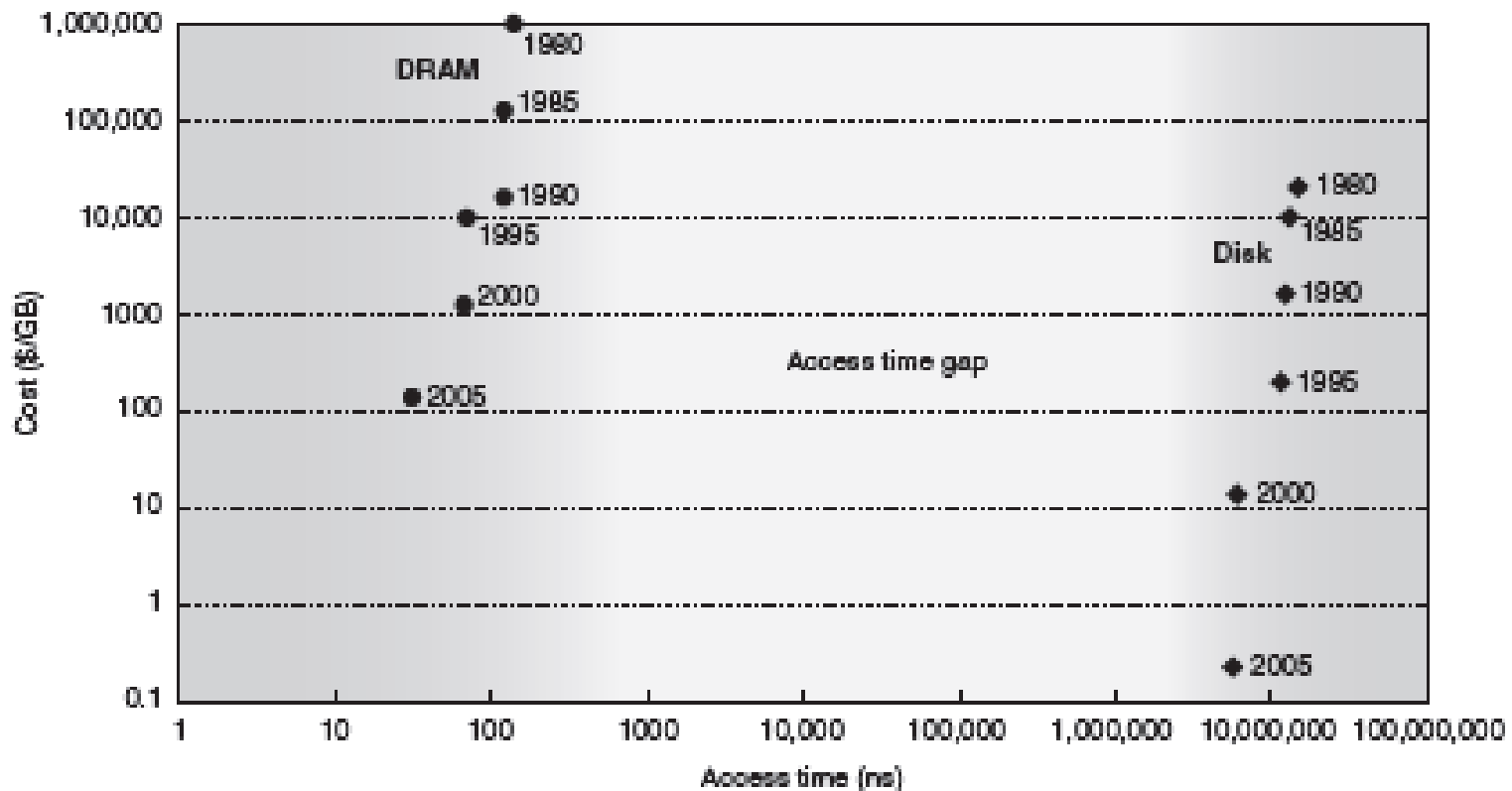


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Disks and main memory

- ▶ The latency of a DRAM memory is 100.000 less than the latency of a disk
- ▶ The cost per GB in a DRAM memory is 30-150 times the cost per GB of a disk
- ▶ In 2015:
 - ▶ An 8 TB disk transfers 190 MB/s at a cost of 250 \$.
 - ▶ An 8 GB DDR4 module transfers 25 GB/s and costs approx. 70\$.

Disks and main memory



Patterson & Hennesy

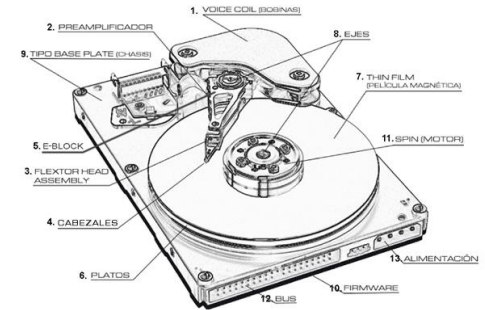
Addressing

- ▶ Types of addressing:
 - ▶ **Physical addressing**: cylinder-track-sector. A sector is determined by these three values.
 - ▶ **Logical blocks addressing (LBN)**
 - ▶ Each sector has a logical number and the mapping is done by the disk
- ▶ Current disk controllers do the mapping between LBN and physical addresses

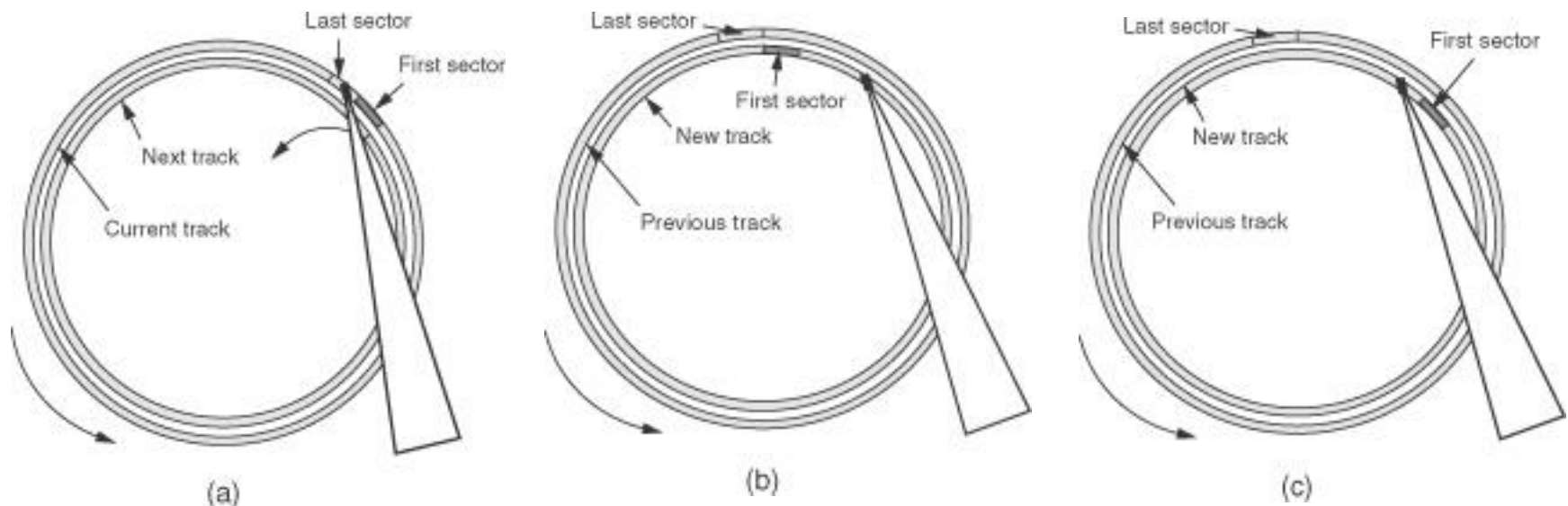
Access time

▶ $T_{\text{access}} = T_{\text{seek}} + T_{\text{latency}} + T_{\text{transfer}}$

- ▶ **Seek time** (T_{seek}): time to move the head from the current cylinder to the target cylinder
- ▶ **Rotational latency** (T_{latency}): time waiting for the rotation of the disk to bring the required sector under the read-write head
 - ▶ $T_{\text{latency}} = \text{Half turn/lap time of a track}$
- ▶ **Data transfer time** (T_{transfer}): time required to traverse a sector and transfer the data from it.
 - ▶ $T_{\text{transfer}} = \text{Amount of data} / \text{data transfer rate}$



Seek and rotation



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Seek time, rotational latency and...

▶ Seek time

- ▶ When the areal density increase the capacity of cylinders increase too:
 - ▶ The probability of reducing the number of seeks is increased
 - ▶ Increase the probability that the next data to request are in the same cylinder, reducing in this way the number of seeks

▶ Rotational latency

- ▶ Rotational latency is generally calculated as half the time it takes the disk to do one revolution:

$$T_{rotate} = \frac{1}{2} \times \frac{60 \times 10^3}{RPM}$$

▶ Zero-latency access

- ▶ Transfer the data as soon as the head is on the desired track to a buffer where the blocks are then reordered.

... and data transfer time

- ▶ Data transfer time can be calculated as:

$$T_{transfer} = \frac{N_{request}}{N_{track}} \times \frac{60}{RPM}$$

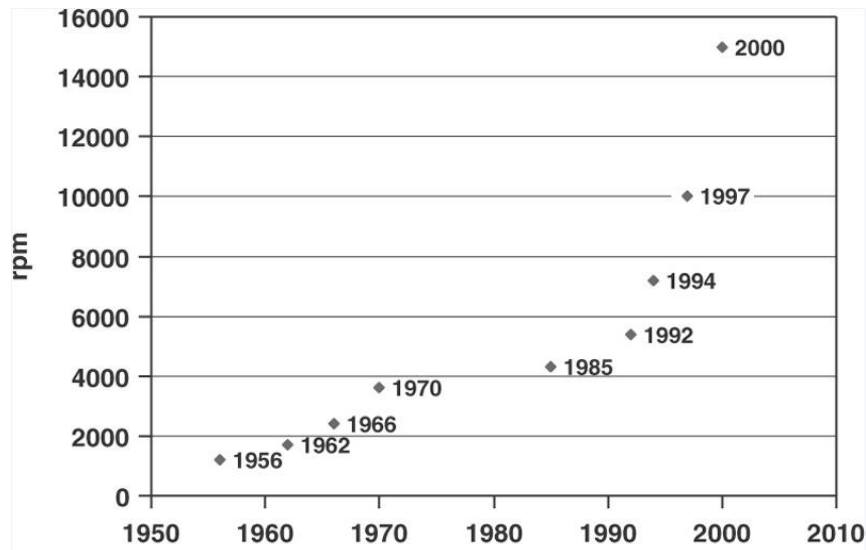
- ▶ Where N_{track} denotes the number of sectors on a track, and $N_{request}$ the data length of a request measured in sectors.
- ▶ The ratio of the sectors of the outmost zone to that of the innermost zone ranges from 1.43 to 1.58.
- ▶ Two elements:
 - ▶ External data rate to measure the transfer rate between memory and disk cache
 - ▶ Transfer rate between disk cache and disk storage media

Rotational latency and rotational speed

Rotational Speed (RPM)	Rotational Latency (ms)
5400	5.6
7200	4.2
10000	3.0
12000	2.5
15000	2.0

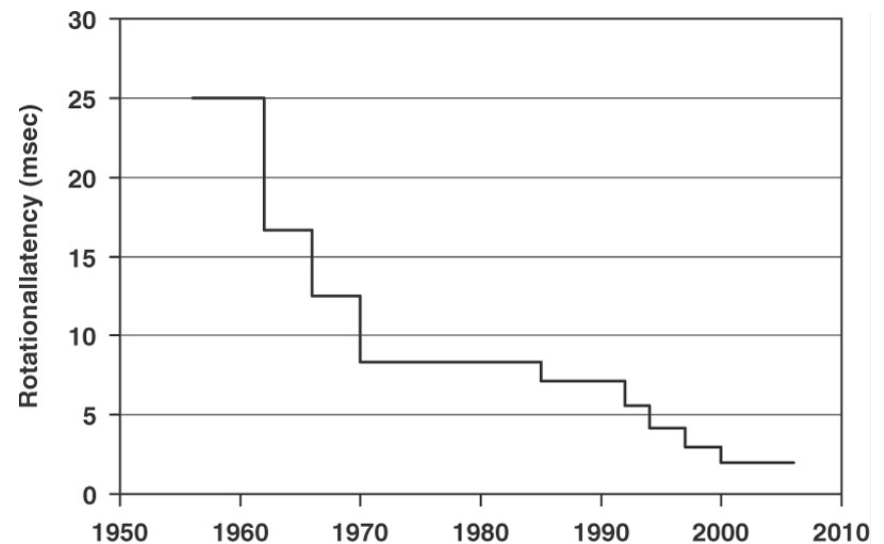
Evolution rotational latency and RPM

RPM



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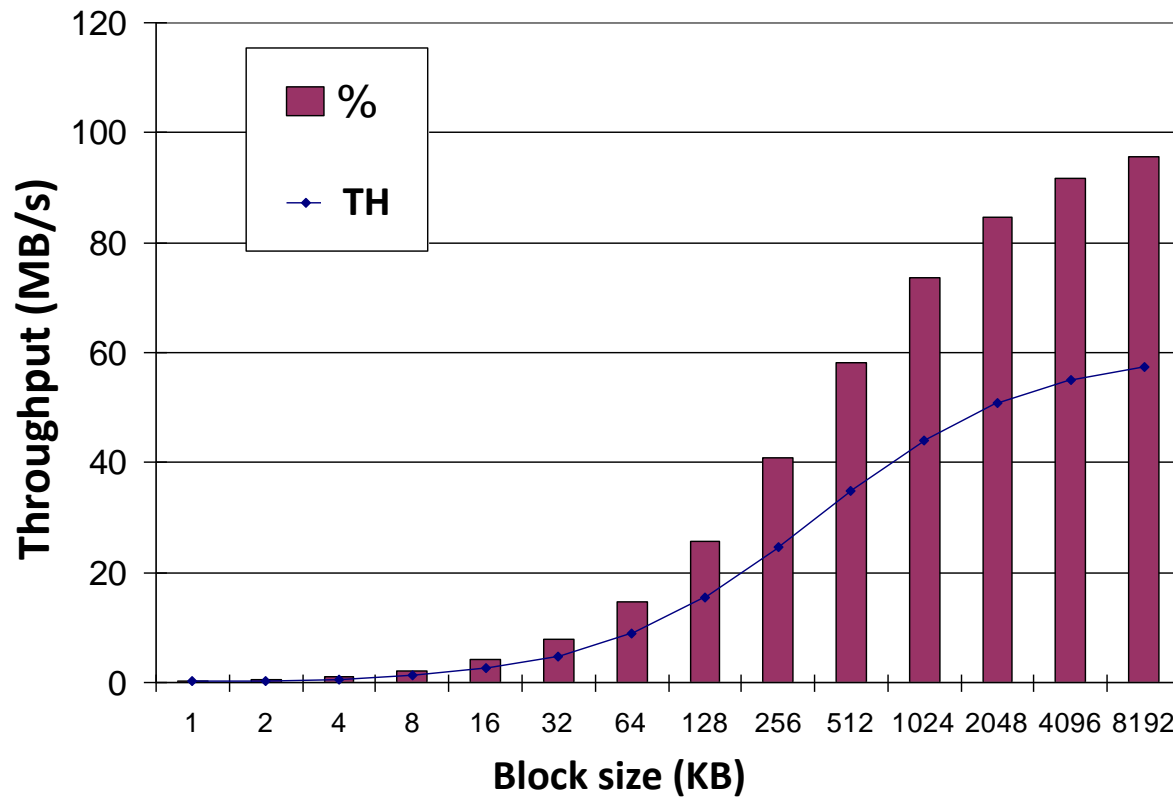
Rotational latency



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Effect of the request size

- Effect of the request size ($t_a=6$ ms y $T_H = 60$ MB/s)



Exercise

- ▶ Consider a disk with:
 - ▶ Rotational speed: 7200 rpm
 - ▶ Disk platters: 5, with 2 surfaces per plate
 - ▶ Number of tracks per plate: 30000
 - ▶ Sectors per plate: 600
 - ▶ Seek time: 1 ms per each 100 tracks
- ▶ If the disk head is in track 0 and the data requested are stored in track 600. Compute:
 - ▶ Capacity of the disk
 - ▶ Rotational latency
 - ▶ Transfer time needed to transfer a sector
 - ▶ Access time for a sector in track 600 (seek time)

Exercise (solution)

- ▶ Capacity:
 - ▶ $5 \text{ plates} * 2 \text{ sides/plates} * 30.000 \text{ tracks/side} * 600 \text{ sector/track} * 512 \text{ bytes/sector} = 85,8 \text{ GB}$
- ▶ Rotational latency:
 - ▶ $L_r = \text{Half turn/lap time of a track}$
 - ▶ $7.200 \text{ rotation/minute} \rightarrow 120 \text{ rotation/second}$
 $\rightarrow 0,0083 \text{ seconds/rotation} \rightarrow 4.2 \text{ milliseconds (half rotation)}$
- ▶ Sector transfer time:
 - ▶ $600 \text{ sectors per track and 1 track is read in } 8,3 \text{ milliseconds}$
 - ▶ $8,3 / 600 \rightarrow 0.014 \text{ milliseconds}$
- ▶ Seek time:
 - ▶ $\text{Every } 100 \text{ tracks } 1 \text{ ms, and it has to seek to the track } 600$
 - ▶ $600 / 100 = 6 \text{ milliseconds}$

Disk controller

- ▶ Circuits and components to control the disk:
 - ▶ Storage interface
 - ▶ Disk sequencer
 - ▶ Error correction code(ECC)
 - ▶ Servo motor
 - ▶ Microprocessor
 - ▶ Buffer controller
 - ▶ Disk cache

Disk cache

- ▶ Exploit the locality
 - ▶ Usually does not exhibit temporal locality due to operating system data caches.
 - ▶ Typically implements read-ahead (prefetch) to improve spatial locality
- ▶ Reduce physical access to disk
 - ▶ Reduce the heat dissipation
 - ▶ Increase the performance

Disk cache

- ▶ Systems designers generally believe that the size of a cache should be at least 0.1 to 0.3 % of the disk.
- ▶ Disk caches are typically divided into independent segments corresponding to sequential data streams
- ▶ Replacement algorithms
 - ▶ Random Replacement
 - ▶ Least Frequently Used (LFU)
 - ▶ Least Recently Used (LRU)

Disk scheduler

- ▶ Disk drives maintain a queue with pending requests
 - ▶ Disk schedulers are designed to minimize the access time by reordering or rearranging pending request in the queue to reduce the seek time and rotational latency
 - ▶ E.g.: block requested: 1, 9, 2, 10 => in queue: 1, 2, 9, 10
- ▶ Scheduling algorithms:
 - ▶ First Come First Served (FCFS)
 - ▶ Shortest Seek Time First (SSTF)
 - ▶ SCAN
 - ▶ C-SCAN
 - ▶ LOOK

Other elements

- ▶ **Disk sequencer**: manages the data transfer between storage interface and data buffer
- ▶ **ECC**: responsible for adding ECC codes to the user data and also checking and correcting errors
- ▶ **Servo control**: detects the current position of the disk head and controls track following and seeking
- ▶ **Microprocessor**: controls the general disk behavior
- ▶ **Buffer controller**: provides arbitration and raw signal control of the buffer memory

Exercise

- ▶ A disk drive has a rotational speed of 7200 rpm and a constant areal density of 604 sectors per track.
The average access time is 4 ms
- ▶ Compute the access time to a sector

Exercise

- ▶ Be a hard disk with an average seek time of 4 ms, a rotation speed of 15 000 rpm and 512-byte sectors with 500 sectors per track. We need to read a file consisting of 2 500 sectors with a total of 1.22 MB. Estimate the time necessary to read this file in two scenarios:
 - ▶ The file is stored sequentially, i.e. the file occupies the sectors of 5 adjacent tracks.
 - ▶ The sectors of the file are randomly distributed on the disk.

Reliability

- ▶ MTTF: mean time to failure
- ▶ MTTR: mean time to repair
- ▶ Availability is defined as:

$$availability = \frac{MTTF}{MTTF + MTTR}$$

- ▶ What does a reliability of 99% mean?
 - ▶ In 365 consecutive days device works $99 \times 365 / 100 = 361.3$ days
 - ▶ It is out of service 3.65 days
- ▶ Failures in disk drives produce the 20-55% of the failures in the storage systems.

Energy consumption

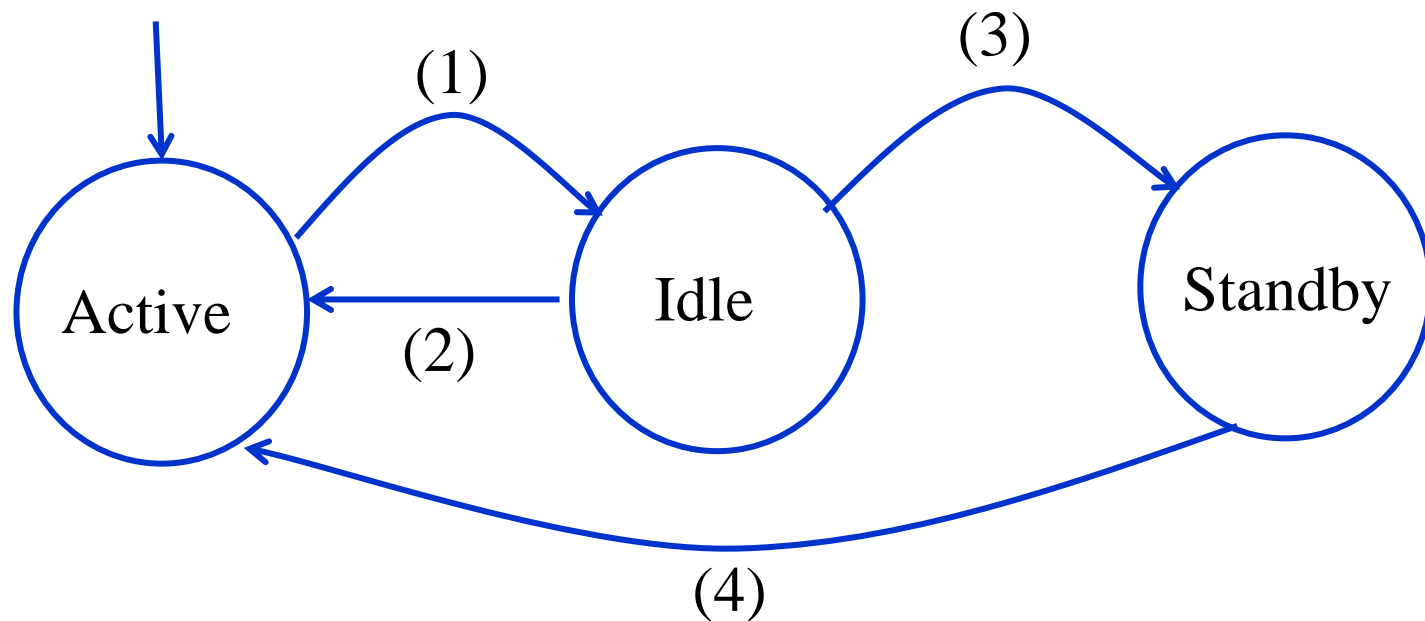
- ▶ The energy consumption in a typical ATA disk drive of 2011 is:
 - ▶ 9 w when is idle
 - ▶ 11 w when is reading or writing
 - ▶ 13 w in a seek operation
- ▶ Power consumed by a disk:

$$Power = N_{platter} \times D_{platter}^{4.6} \times RPM^{2.8}$$

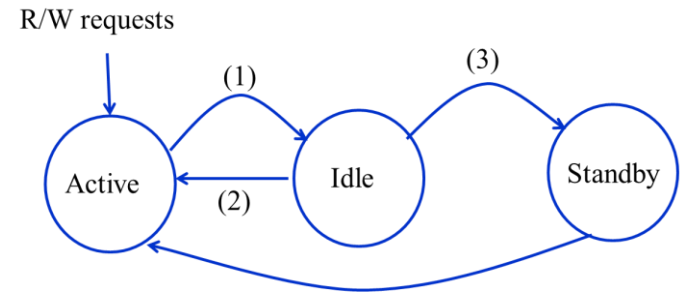
- ▶ Where $N_{platter}$ is the number of disk patters y $D_{platter}$ the diameter for the platters
- ▶ Temperature is often the most important factor which affects the reliability of disk drives
 - ▶ Every 10° increase over 21° decreases the reliability by 50%

Power state transition of disk drives

R/W requests



Power state transitions



1. There is no pending request.
 - ▶ the disk drive is transferred to the idle state (where)
 - ▶ the disk platters are still spinning but the electronics may be partially unpowered
2. Disk drive receives a request.
3. To conserve energy
 - ▶ the disk drive is transferred to the standby state (where)
 - ▶ the disk stops spinning, and the head is moved off the disk
4. To perform requests after entering the standby state, the disk drive must be transferred back from the standby state to the active state by spinning up

Energy conservation methods

- ▶ Based on timeout strategies. Once a disk drive is idle for a specific period of time, the disk drive is spun down to save energy
- ▶ Dynamic prediction. Based on the behaviors of application
- ▶ Stochastic mechanisms.
- ▶ Application-aware power management
 - ▶ Applications inform over the access pattern (in the source code or with compiler-driven methods)

Impacts of power state transitions

problems spinning down disks

- ▶ Increased consumption, when the platens have to rotate again.
- ▶ Reduces the reliability of the discs.
Manufacturers usually indicate the number of start/stop cycles a disk can withstand. Above this value the probability of failure increases by 50%.
- ▶ Power saving methods are usually applied to portable devices and are not applied to servers because of the intensive data loads.

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4. **Case study:** hard disk drive and **solid-state drives**
5. I/O interaction: I/O techniques

Solid State Drive (SSD)

- ▶ Semiconductor-based block storage device that acts as a disk drive
 - ▶ Based on Flash memories
 - ▶ Non-volatile storage
 - ▶ Based on DDR memories
 - ▶ Requires batteries and disk backup for non-volatile storage

HDD

with moving parts



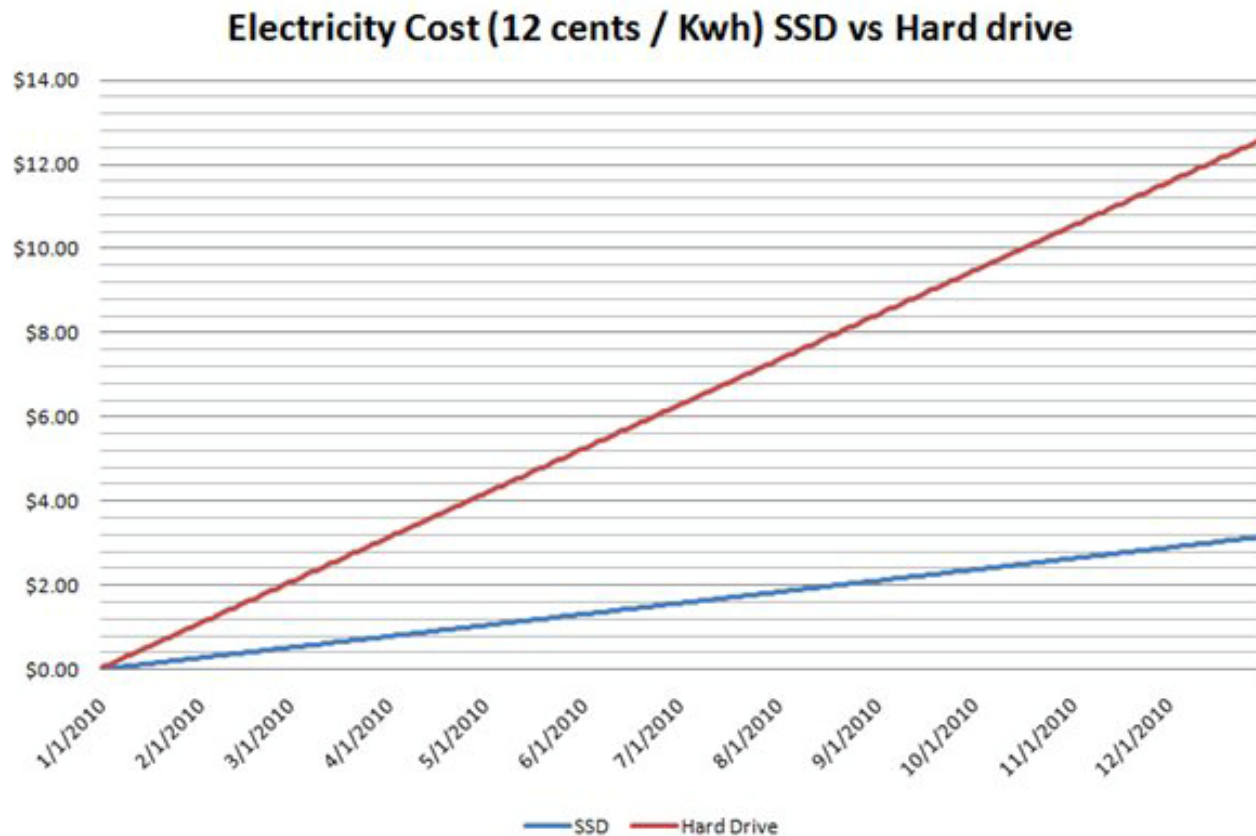
SDD

Without moving parts

SDD vs HDD

	SDD	HDD
Access time	0.1 ms	5-8 ms
I/O operations/sec	6000 io/s	400 io/s
consumption	2-5 watts	6-15 watts

SDD vs HDD: energy consumption



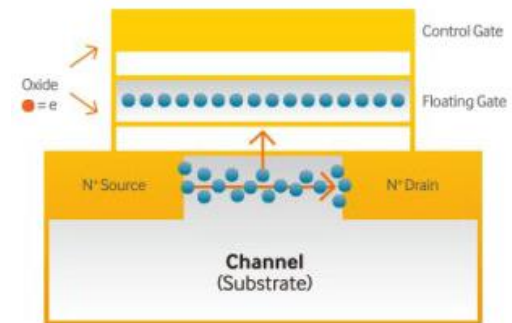
Flash Memories

- ▶ Non-volatile memories that can be deleted and recorded electrically
- ▶ Types:

Flash NOR	NAND Flash
<ul style="list-style-type: none">▶ Based on NOR gates▶ Allows byte level access▶ Good for high-speed random access▶ Used in BIOS memory (boot function)▶ Faster reading operations	<ul style="list-style-type: none">▶ Based on NAND gates▶ Cannot access individual bytes▶ Reads and writes at high speed in sequential mode at block level▶ Higher density and cheaper. Used in SSD▶ More durable, less expensive, denser, faster write/erase operations

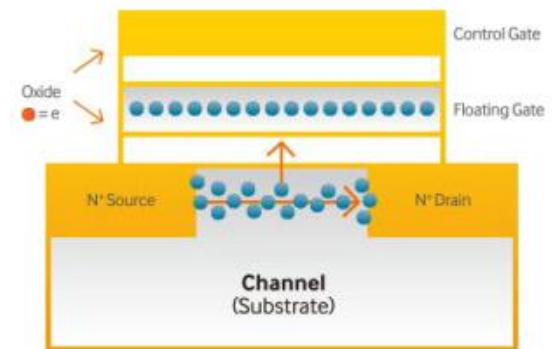
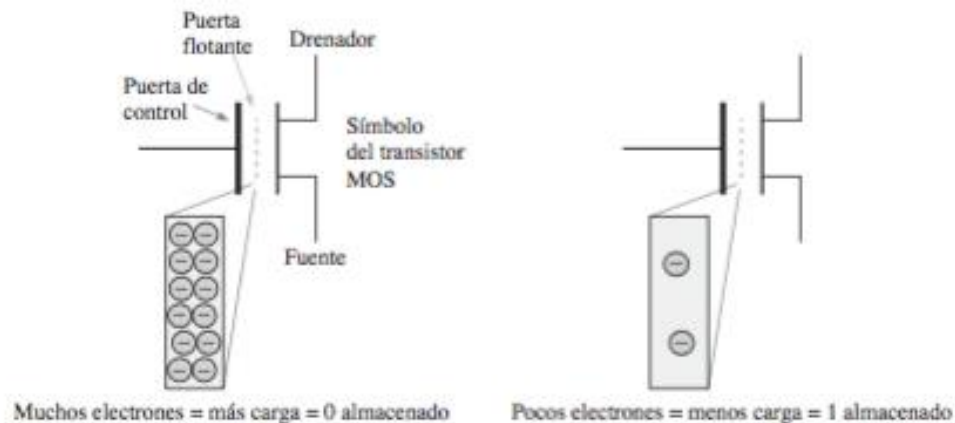
Memory cells

- ▶ Each storage cell consists of a floating gate MOS transistor
- ▶ There are two gates insulated by a layer of oxide
 - ▶ Control gate
 - ▶ Floating gate
- ▶ The electrons flow freely between the two gates
- ▶ The floating gate is electrically insulated, trapping the electrons



Memory cells

- ▶ The data bit is stored as a charge or no charge in the floating gate, depending on whether you want to store a 0 or a 1.

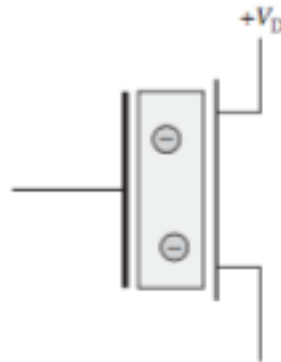
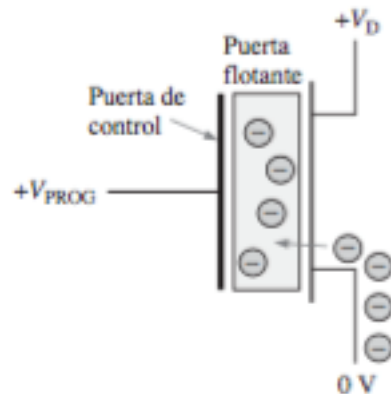


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Basic operations of a flash memory cell

- ▶ Programming
 - ▶ Initially all cells are in state 1, because the charge is removed
- ▶ Read operation
- ▶ Delete operation

Programming a Flash memory cell

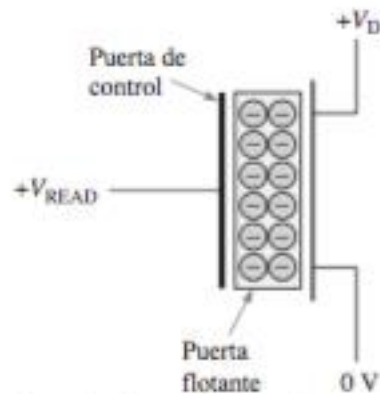


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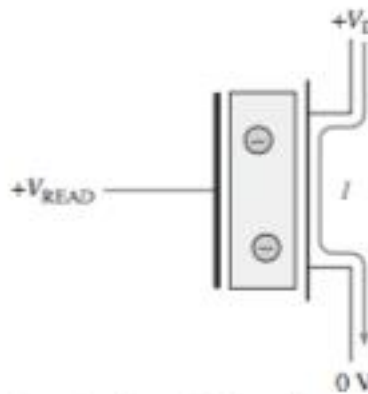
- ▶ To store a 0, a sufficiently positive voltage is applied to the control gate with respect to the source, to add charge to the floating gate during programming (attracts electrons)
- ▶ In the writing process, electrons are added to those gates that should store a 0 and not added to those that should store a 1.
- ▶ Only "0" is written
- ▶ To store a 1, no charge is added, leaving the cell in the deleted state

Reading a Flash memory cell

- Positive voltage is applied to the control gate



Cuando se lee un 0, el transistor permanece desactivado, porque la carga de la puerta flotante impide a la tensión de lectura exceder el umbral de activación.

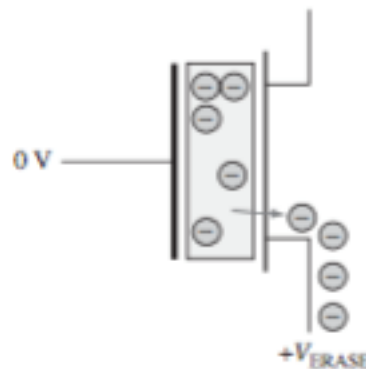


Cuando se lee un 1, el transistor se activa, porque la ausencia de carga en la puerta flotante permite que la tensión de lectura exceda el umbral de activación.

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Delete

- ▶ During the delete operation, the charge is removed from all memory cells. A voltage is applied in the opposite direction to remove the electrons



Para borrar una célula, se aplica a la fuente una tensión suficientemente positiva con respecto a la puerta de control, con el fin de extraer la carga de la puerta flotante durante la operación de borrado.

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NAND Flash memory types

- ▶ Single-level cell flash (SLC)
 - ▶ Store 1 bit per cell
 - ▶ 50000 - 100000 writings per cell
 - ▶ Used primarily in military and industrial applications
- ▶ Multi-level cell flash (MLC)
 - ▶ Store several bits per cell, depending on the number of electrons stored in the cell
 - ▶ They offer more capacity but less duration (they wear more)
 - ▶ < 10000 writings per cell
 - ▶ Used in consumer electronics
 - ▶ Lower cost
 - ▶ Half the performance of SLCs

Wear leveling

▶ Problem:

- ▶ A NAND flash memory can only write a certain number of times in each block (or cell)
- ▶ When the limit is exceeded, the cell wears out (its oxide layer) and no longer stores electrons properly

▶ Solution: Wear Leveling

- ▶ A process used by an SSD controller to maximize the life of the flash memory
- ▶ This technique levels out the wear and tear on all blocks by distributing the data writing across all blocks
 - ▶ When a block is to be modified, it is written in a new one

Structure of a Nand Flash

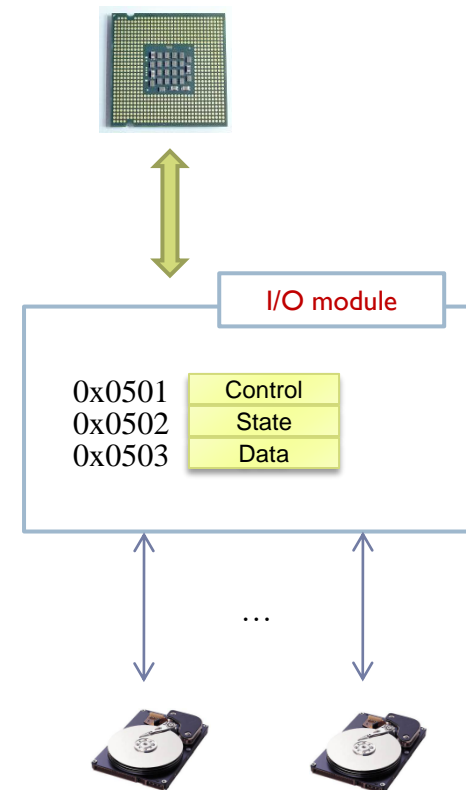
- ▶ NAND flashes are divided into 128 KB blocks that are subdivided into 2KB pages
- ▶ The deletion is done from a complete block
- ▶ Programming and reading a page

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4. Case study: hard disk drive and solid-state drives
5. I/O interaction: I/O techniques

I/O module: main characteristics

- ▶ **Transfer unit**
 - ▶ Block
 - ▶ Character
- ▶ **Addressing**
 - ▶ Memory-mapped I/O
 - ▶ Port-mapped I/O
- ▶ **I/O techniques**
 - ▶ Programmed I/O
 - ▶ Interrupt I/O
 - ▶ DMA



Characteristics (1/3):

Transfer unit

- ▶ **Transfer unit**
 - ▶ Block
 - ▶ Character
- ▶ **Addressing**
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 - ▶ DMA

▶ **Block devices:**

- ▶ Unit: **block** of bytes
- ▶ Access: **sequential** or **random**
- ▶ Operations: read, write, seek, ...
- ▶ Examples: “tapes” and disks



▶ **Character devices:**

- ▶ Unit: **chars** (ASCII, Unicode, etc.)
- ▶ Access: **sequential** to characters
- ▶ Operations : get, put,
- ▶ Example: terminals, printers, etc.



Characteristics (2/3):

I/O addressing

▶ **Memory-mapped I/O (MMIO)**

- ▶ I/O registers are mapped in memory using a set of memory addresses for these registers.
- ▶ Same machine instructions for memory and I/O:

- `lw $a0, label2_disk1`

- Load in the processor register “\$a0” the value stored in the I/O register identified by a given address “label2_disk1”

- `sw $a0, label_disk2`

- To write an item in an I/O register from the I/O module

▶ **Port-mapped I/O (PMIO):**

- ▶ I/O address space is isolated from memory address space.

- ▶ Special privileged machine instructions (~ to lw/sw):

- `IN $a0, label2_disk1`

- Load in the processor register “\$a0” the value stored in the I/O register identified by a given address “label2_disk1”

- `OUT $a0, label_disk2`

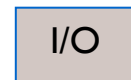
- To write an item in an I/O register from the I/O module

- ▶ **Transfer unit**
 - ▶ Block
 - ▶ Character
- ▶ **Addressing**
 - ▶ Memory-mapped I/O
 - ▶ Port-mapped I/O
- ▶ **I/O techniques**
 - ▶ Programmed I/O
 - ▶ Interrupt I/O
 - ▶ DMA

`lw Reg., add.`
`sw Reg., add.`



`in Reg., add.`
`out Reg., add.`



`lw Reg., add.`
`sw Reg., add.`



Characteristics (3/3)

I/O techniques: interaction CPU - I/O module

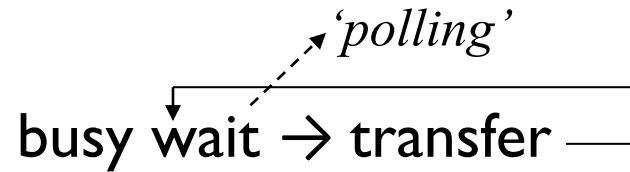
- ▶ Transfer unit
 - ▶ Block
 - ▶ Character
- ▶ Addressing
 - ▶ Memory-mapped I/O
 - ▶ Port-mapped I/O
- ▶ I/O techniques
 - ▶ Programmed I/O
 - ▶ Interrupt I/O
 - ▶ DMA

▶ Programmed I/O

- ▶ CPU does all I/O:

busy wait → transfer —

'polling'



▶ Interrupt I/O

- ▶ CPU does not wait, only transfer data

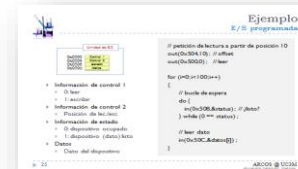
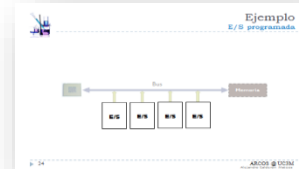
▶ DMA (Direct Memory Access) I/O

- ▶ CPU neither wait, nor transfer, it is notified at the end

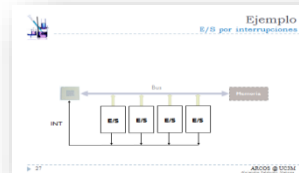
Characteristics (3/3)

I/O techniques: interaction CPU - I/O module

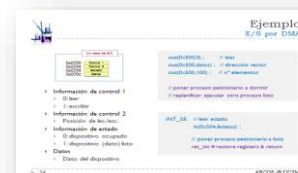
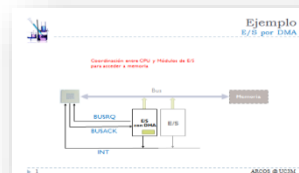
▶ Programmed I/O



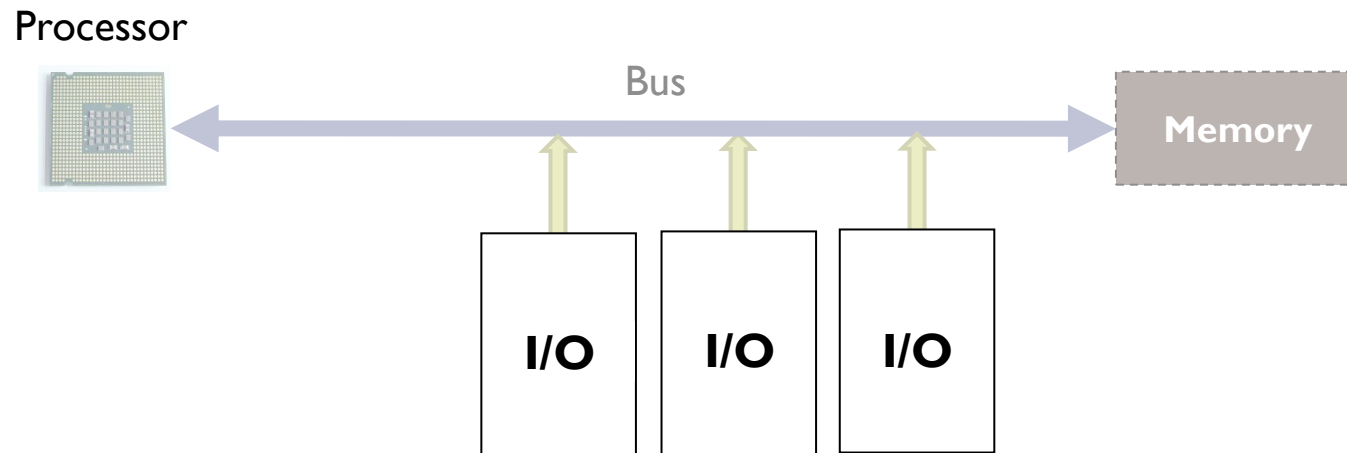
▶ Interrupt I/O



▶ DMA I/O

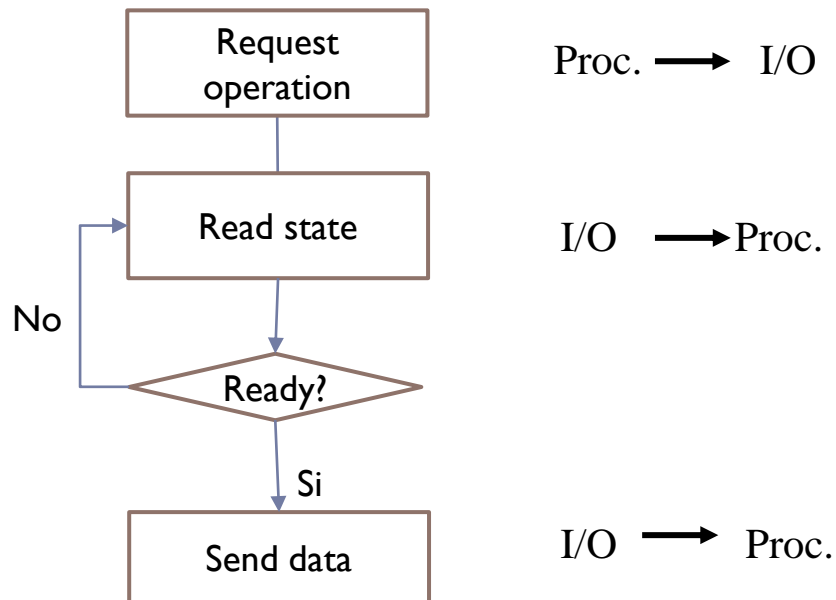


Programmed I/O



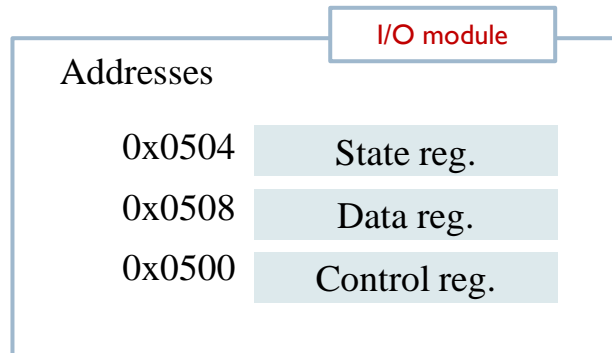
Programmed I/O

example of interaction for single request



Programmed I/O

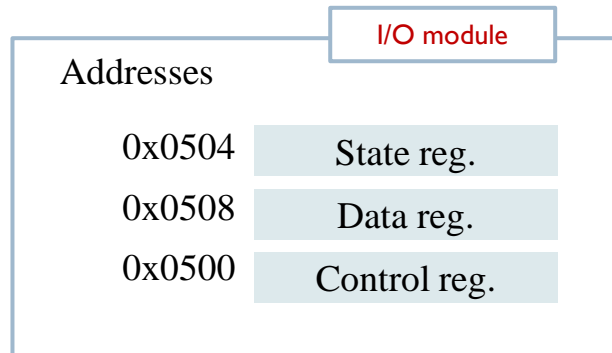
example of interaction for single request



- ▶ Control information:
 - ▶ 0: read
 - ▶ 1: write
- ▶ State information:
 - ▶ 0: device not ready
 - ▶ 1: device (data) ready
- ▶ Memory-mapped I/O:
 - ▶ lw and sw MIPS instructions

Programmed I/O

example of interaction for single request



- ▶ Control information:
 - ▶ 0: read
 - ▶ 1: write
- ▶ State information:
 - ▶ 0: device not ready
 - ▶ 1: device (data) ready
- ▶ Memory-mapped I/O:
 - ▶ lw and sw MIPS instructions

▶ How to read a data (word)?

1. Send the command

```
li $t0, 0
sw $t0, 0x0500
```

2. Read state

```
bucle: lw $t0, 0x0504
```

3. Check state

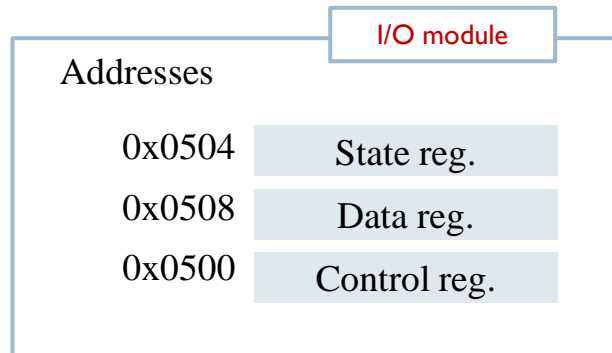
```
beqz $t0, bucle
```

4. Read the data (word)

```
lw $t0, 0x0508
```

Programmed I/O

example of interaction for single request



- ▶ Control information:
 - ▶ 0: read
 - ▶ 1: write
- ▶ State information:
 - ▶ 0: device not ready
 - ▶ 1: device (data) ready
- ▶ Memory-mapped I/O:
 - ▶ lw and sw MIPS instructions

▶ How to write a data (word)?

1. Send the command

```
li $t0, 123
sw $t0, 0x0508
```

2. Send the command

```
li $t0, 1
sw $t0, 0x0500
```

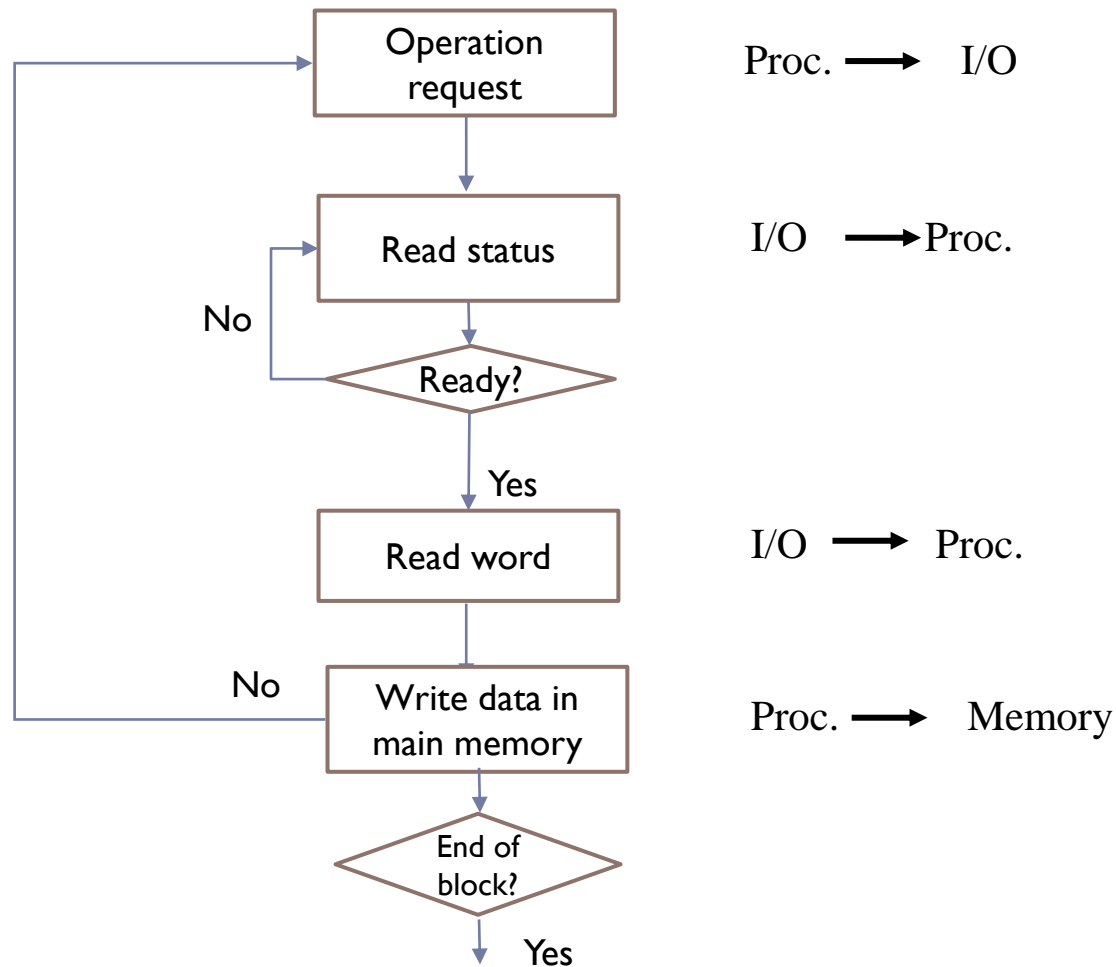
3. Read state

```
bucle: lw $t0, 0x0504
```

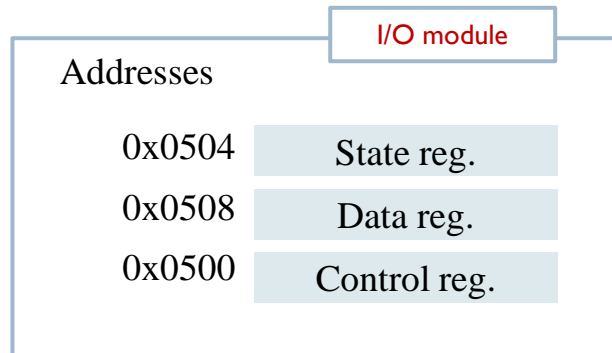
4. Check state

```
beqz $t0, bucle
```

Reading a data block



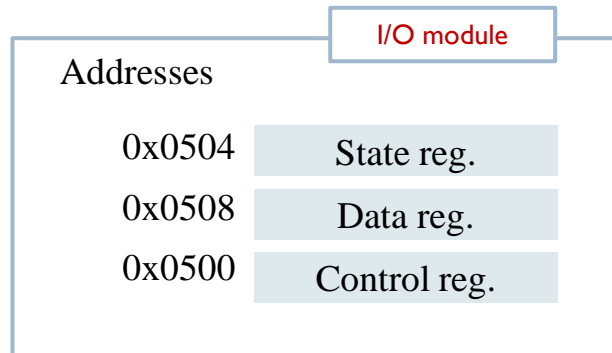
Exercise



- ▶ Control information:
 - ▶ 0: read
 - ▶ 1: write
- ▶ State information:
 - ▶ 0: device not ready
 - ▶ 1: device (data) ready
- ▶ Memory-mapped I/O:
 - ▶ lw and sw MIPS instructions

Code an assembler program that reads 100 integers using the described I/O module, and stores them in the main memory at address given by the 'dataI' label.

Exercise (solution)



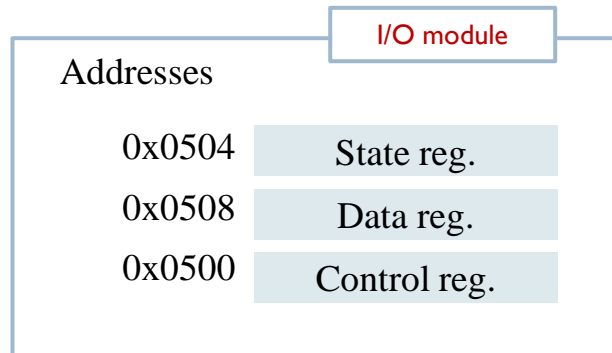
- ▶ Control information:
 - ▶ 0: read
 - ▶ 1: write
- ▶ State information:
 - ▶ 0: device not ready
 - ▶ 1: device (data) ready
- ▶ Memory-mapped I/O:
 - ▶ lw and sw MIPS instructions

```
.data
    data1: .space 400

.text
.globl main
main:    li $t3 0
        loop1: li $t0 0
                sw $t0 0x500

        loop2: lw $t1 0x504
                beqz $t1 loop2
                lw $t2 0x508
                sw $t2 data1($t3)
                add $t3 $t3 4
                bne $t3 400 loop1
```

Exercise (solution)



- ▶ Control information:
 - ▶ 0: read
 - ▶ 1: write
- ▶ State information:
 - ▶ 0: device not ready
 - ▶ 1: device (data) ready
- ▶ Memory-mapped I/O:
 - ▶ lw and sw MIPS instructions

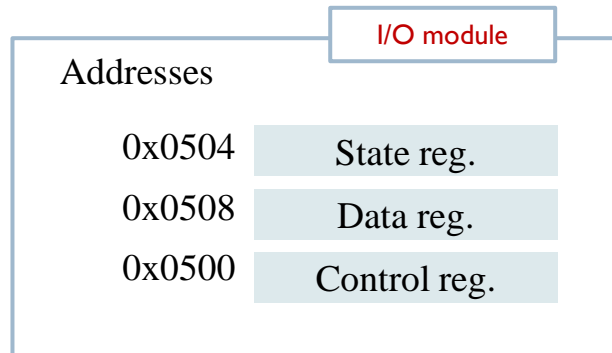
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            bne $t3 400 loop1
```

} Synchronization loop

Exercise (solution)



- ▶ Control information:
 - ▶ 0: read
 - ▶ 1: write
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```

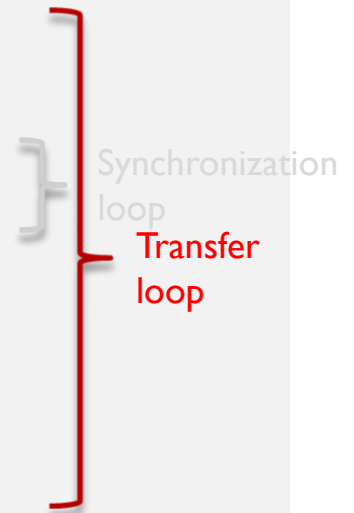
} Synchronization loop

} Transfer loop

Exercise

- ▶ Be a computer with the capacity to execute 200 million instructions per second (200 MIPS).
- ▶ The I/O module described above is connected with an average read timeout of 5 ms.
- ▶ Calculate how many instructions are executed in the synchronization loop and in the transfer loop for the program shown.

```
.data
    data1: .space 400
.text
.globl main
main:    li $t3 0
        loop1: li $t0 0
            sw $t0 0x500
        loop2: lw $t1 0x504
            beqz $t1 loop2
            lw $t2 0x508
            sw $t2 data1($t3)
            add $t3 $t3 4
            bne $t3 400 loop1
```



Exercise (solution)

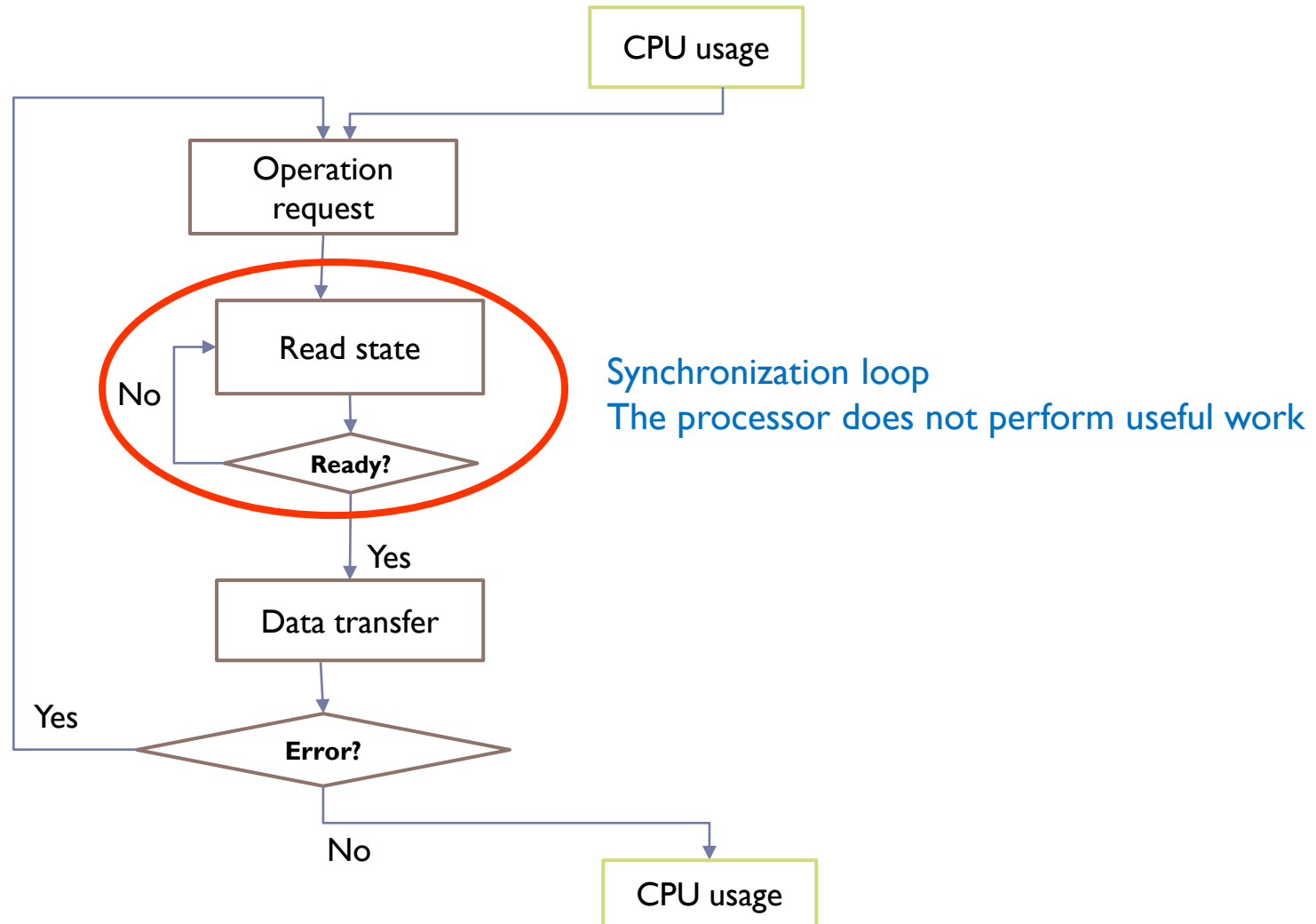
- ▶ Bucle de sincronización:
 - ▶ In average 5 ms
 - ▶ 200 MIPS are executed
 - ▶ $I_{bs} = 200 * 10^6 * 5 * 10^{-3} = 10^6$
- ▶ Bucle de transferencia:
 - ▶ $I = (li \$t3\ 0) + 6 * 100 + 10^6 (I_{bs})$
- ▶ 1,000,601 instructions are executed, and 1,000,000 are instructions executed in the synchronization loop (el 99,9%)
 - ▶ It is a waste of processor cycles
 - ▶ The CPU does not perform useful work

```
.data
    data1: .space 400
.text
.globl main
main:    li $t3 0
        loop1: li $t0 0
            sw $t0 0x500
        loop2: lw $t1 0x504
            beqz $t1 loop2
            lw $t2 0x508
            sw $t2 data1($t3)
            add $t3 $t3 4
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```

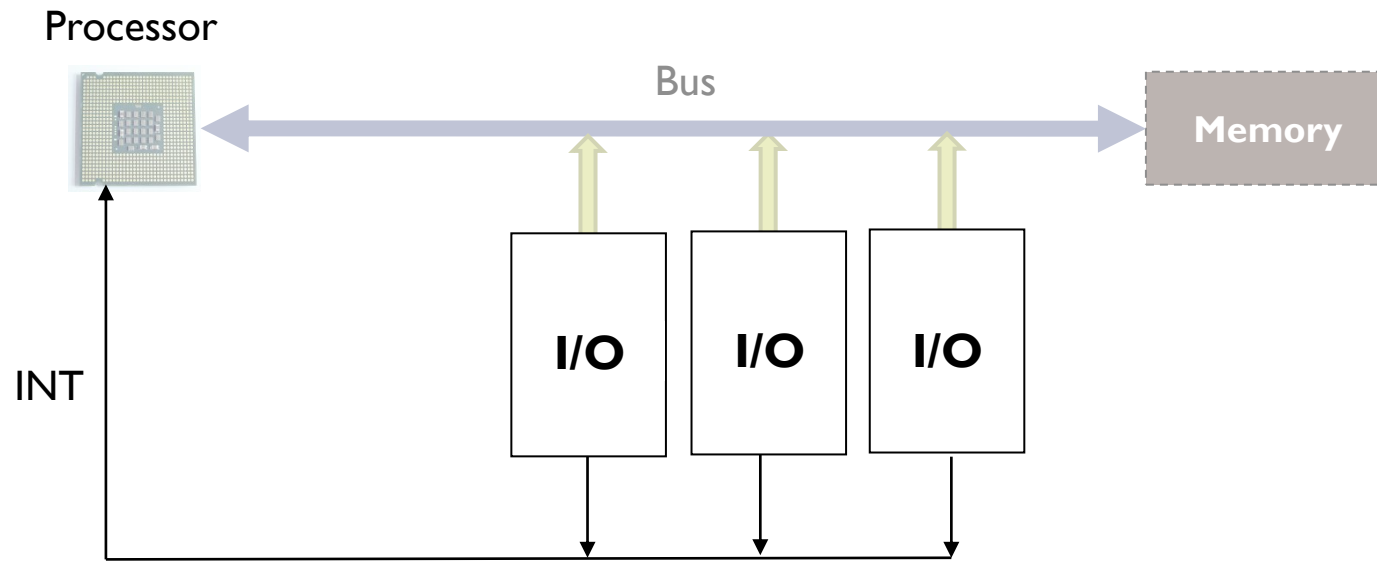
Synchronization loop

Transfer loop

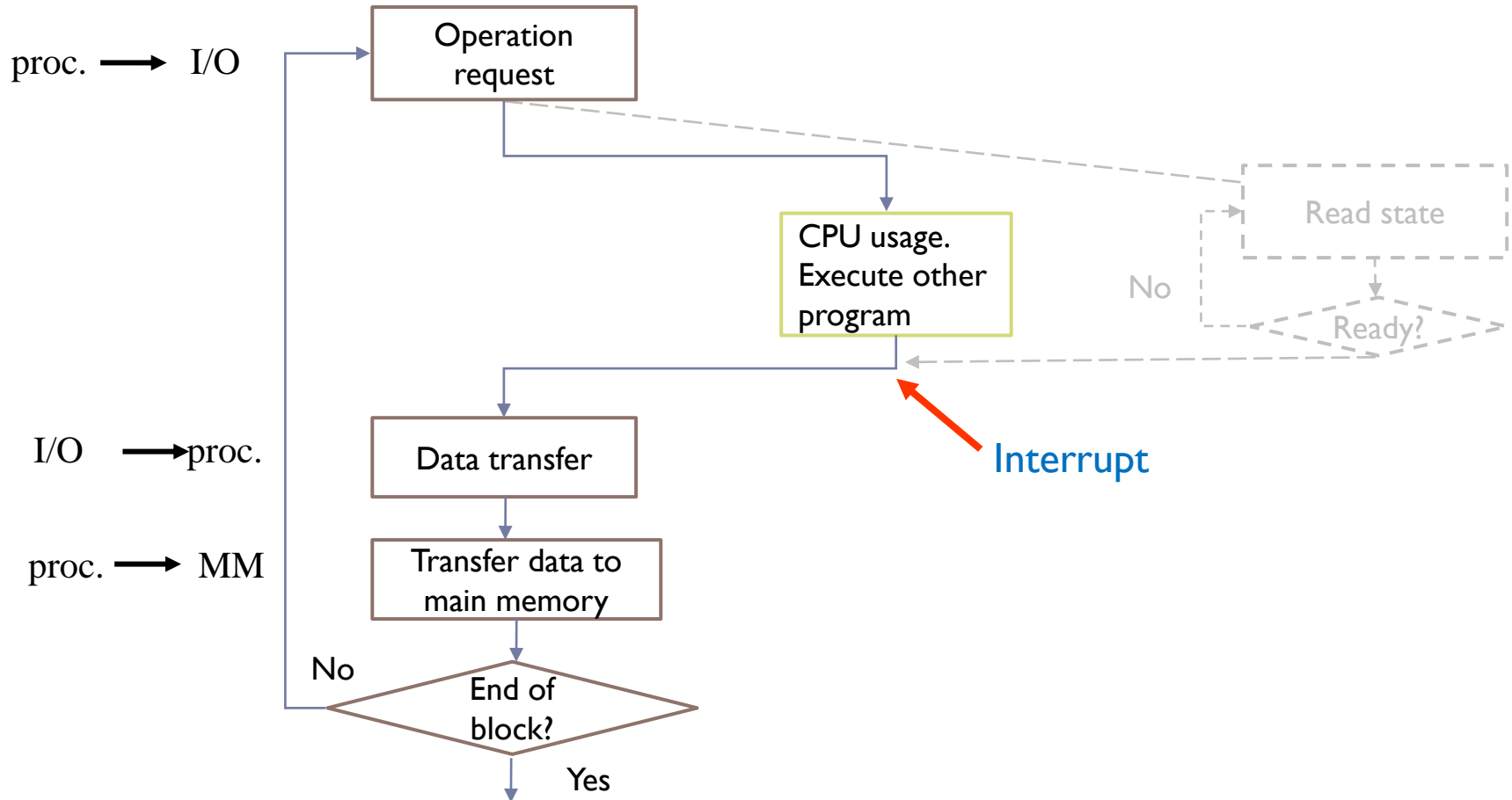
Main problem of the programmed I/O



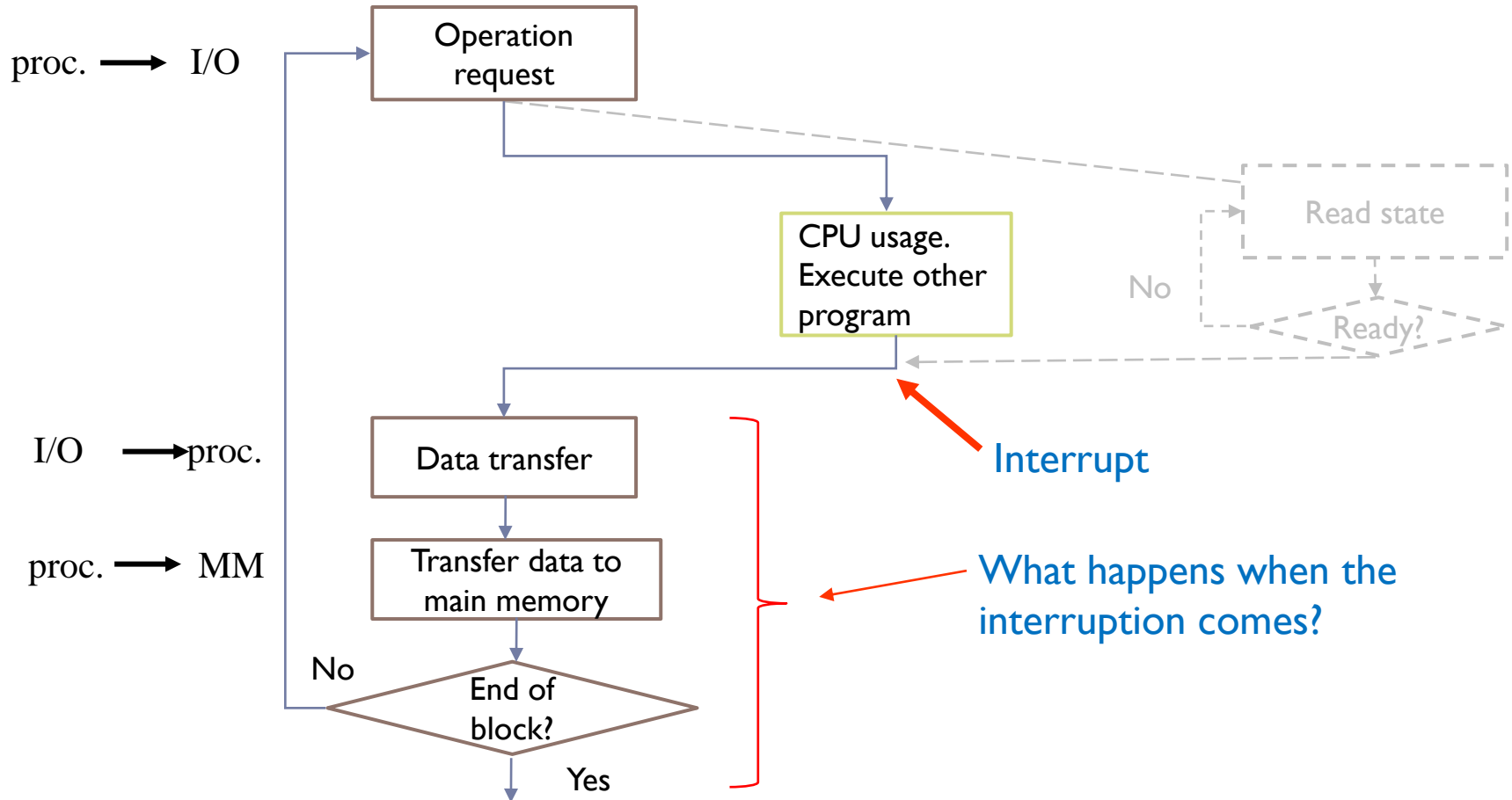
Interrupt driven I/O



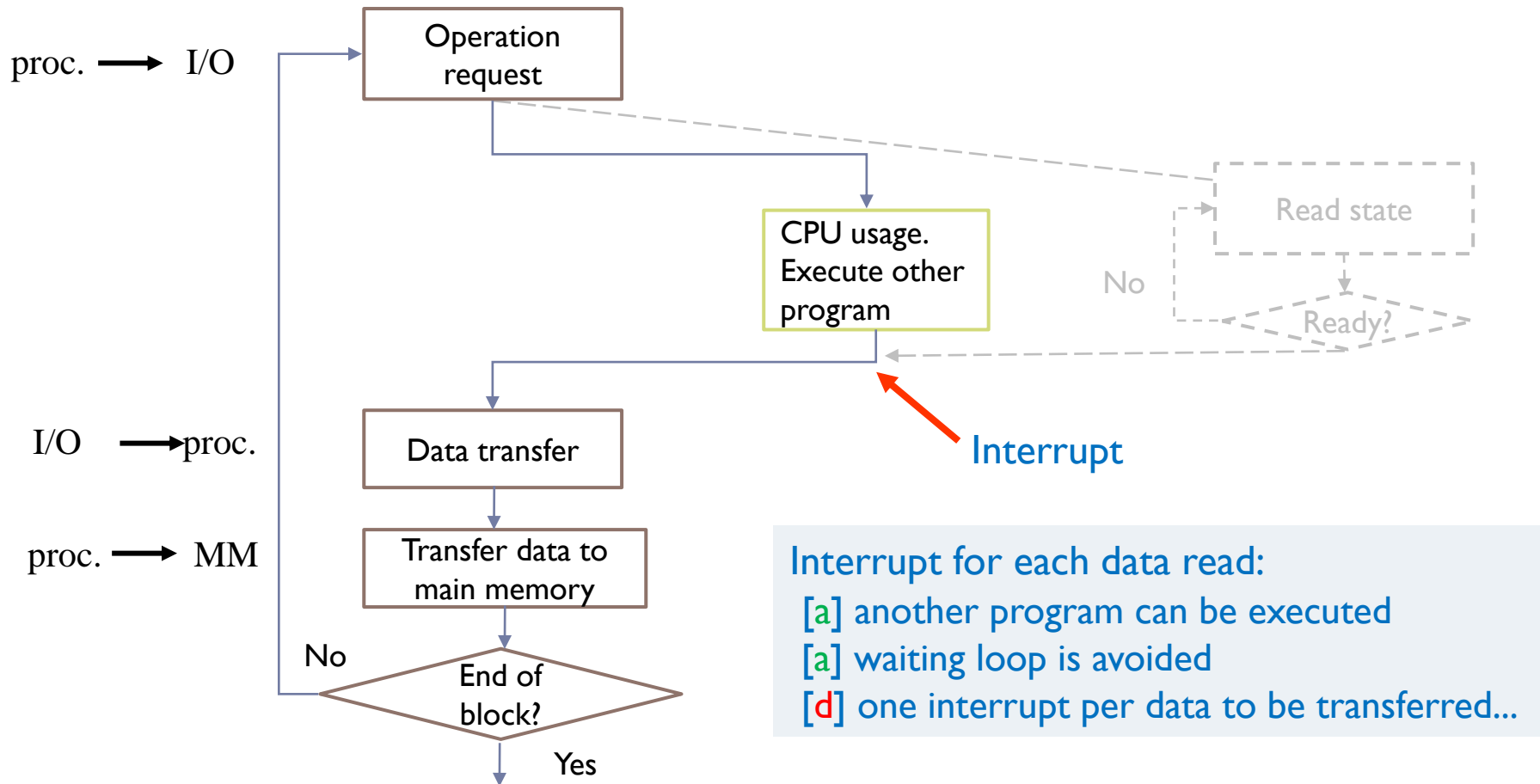
Interrupt I/O



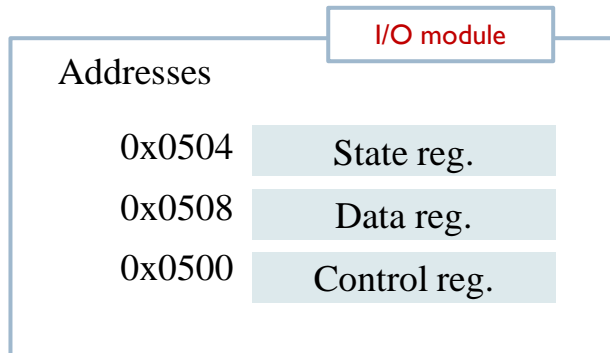
Interrupt I/O



Interrupt I/O



Example



- ▶ Control information:
 - ▶ 0: read
 - ▶ 1: write
- ▶ State information:
 - ▶ 0: device not ready
 - ▶ 1: device (data) ready
- ▶ Memory-mapped I/O:
 - ▶ lw/sw MIPS instructions

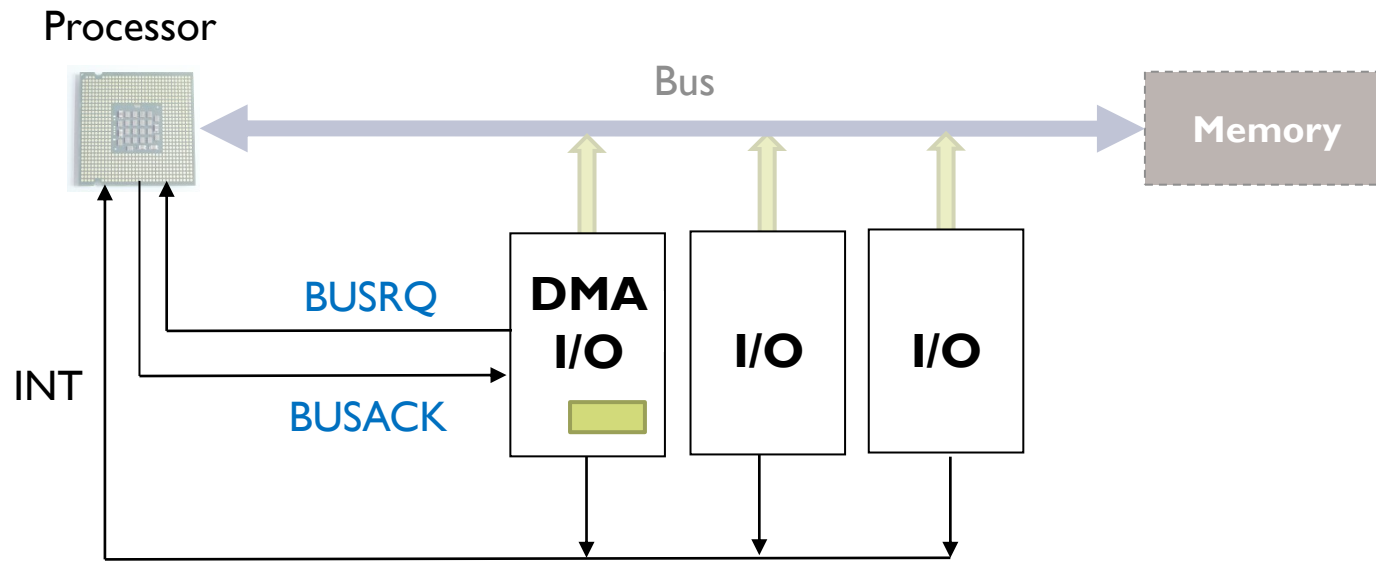
request:

```
// read request
p.counter = 0;
p.neltos = 100;
out(0x500, 0) ; // request read first element
// Voluntary context switching (V.C.S.)
```

INT_05:

```
in(0x508, &(p.status)) ;           // read state
in(0x50C, &(p.data[p.counter])) ; // read data
if ((p.counter < p.neltos) && (p.status == OK)) {
    p.counter++ ;
    out(0x500, 0) ; // request read next elto.
} else { // process.state to READY }
return_interrupt # restore registers & return
```

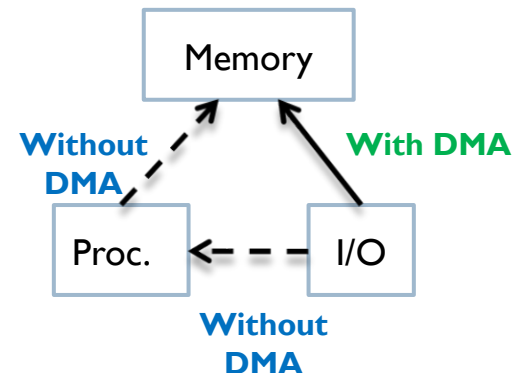
DMA I/O



- ▶ A coordination is needed to control the access to memory from the processor and I/O modules

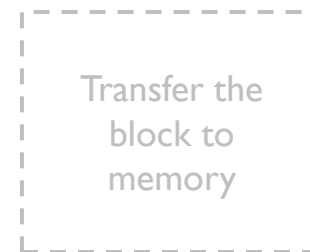
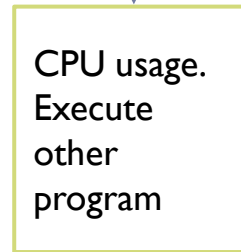
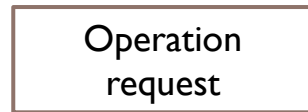
DMA I/O

- ▶ DMA: Direct Memory Access
- ▶ CPU does not carry out the transfer between the I/O module and the memory
 - ▶ With interrupts the synchronization loop is avoided, but the transfer is carry out by CPU
 - ▶ For a block with N bytes, N interrupts are needed
- ▶ Using DMA, the whole transfer is done by the I/O module
 - ▶ Only **one** interrupt at the end

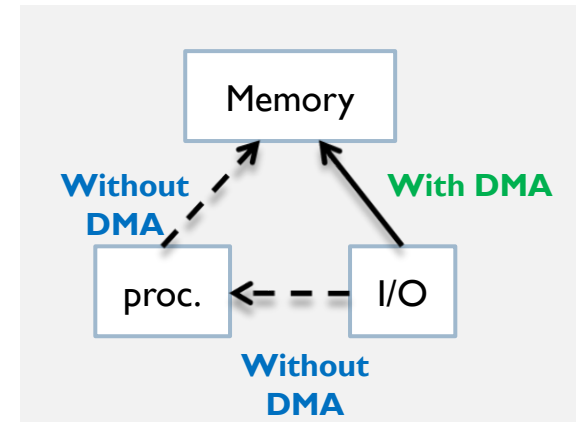


Transfer a block using DMA

Proc. → I/O

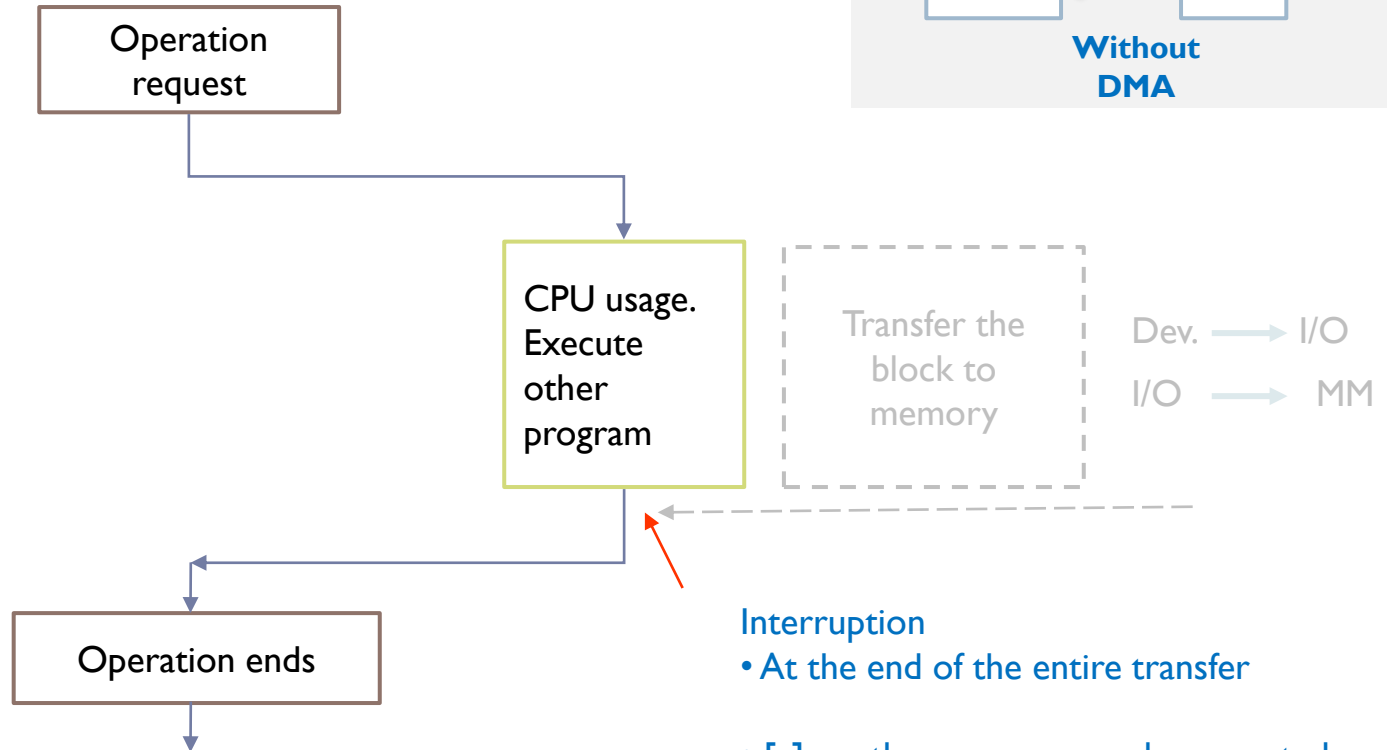


Dev. → I/O
I/O → MM



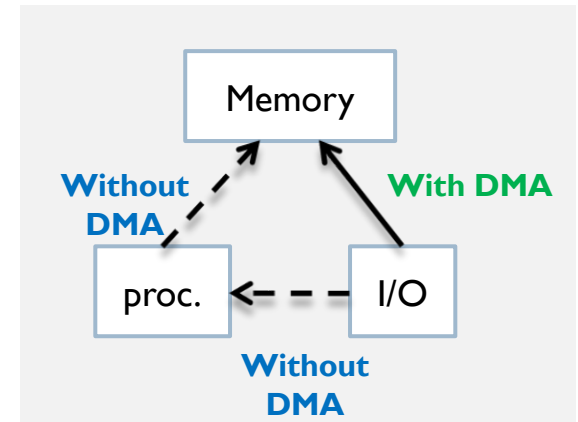
Transfer a block using DMA

Proc. → I/O

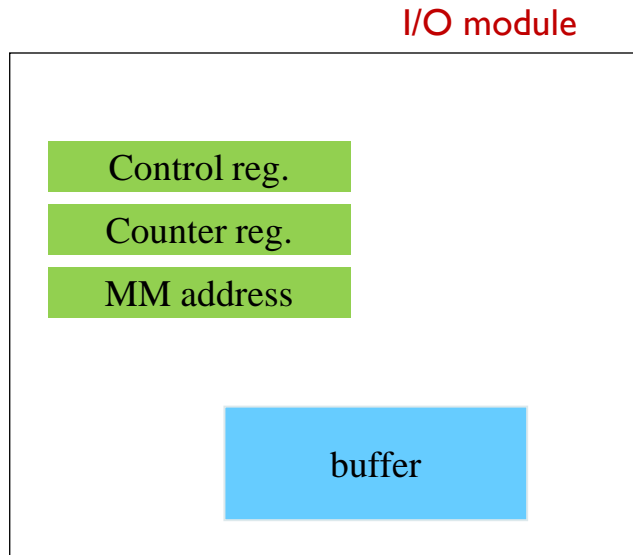


Interruption

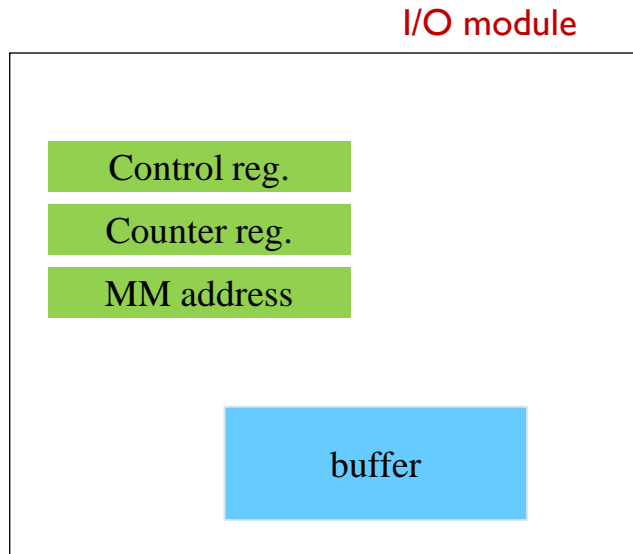
- At the end of the entire transfer
- [v] another program can be executed
- [v] a single interrupt



Simplified structure of I/O module for DMA



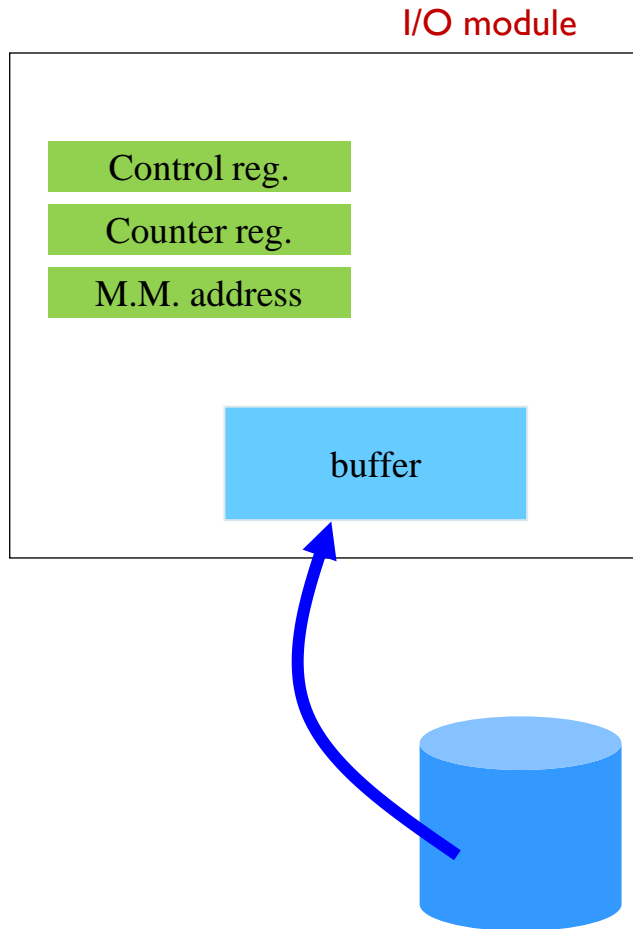
Data transfer with DMA



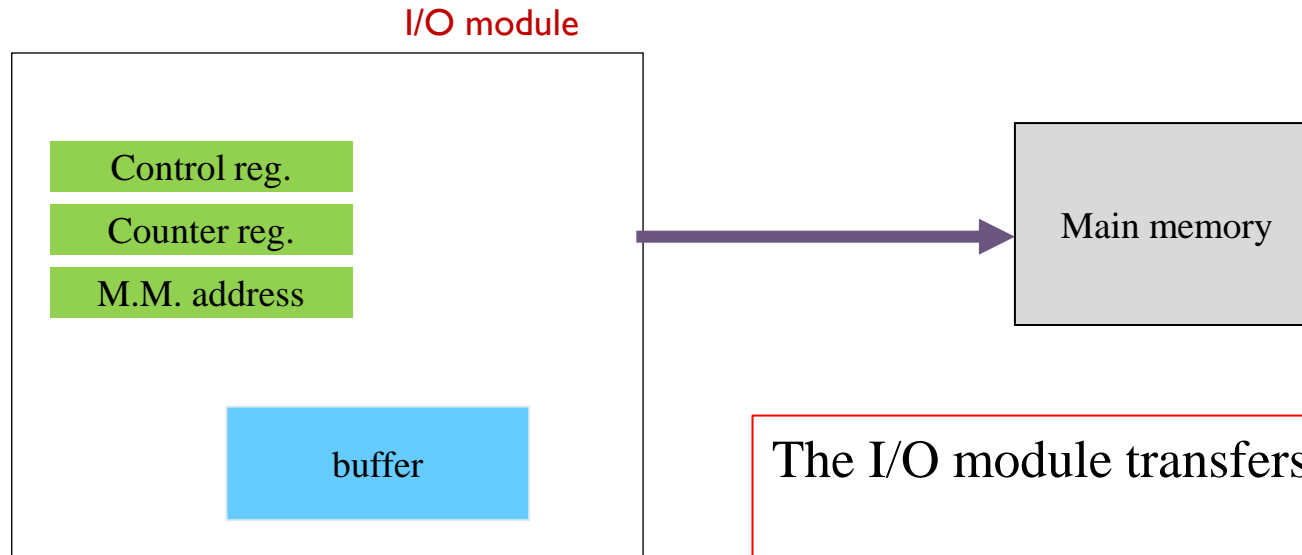
- ▶ The processor writes in I/O registers (using I/O instructions)
 - ▶ Operation (**control reg.**)
 - ▶ Read, write, etc.
 - ▶ The number of bytes to transfer (**counter reg.**)
 - ▶ **Memory address** where:
 - ▶ Data are stored (write in device)
 - ▶ Store the data (reading from device)

Data transfer with DMA

- ▶ I/O module transfers the data block from the device to the internal buffer inside the I/O module (in a reading operation)



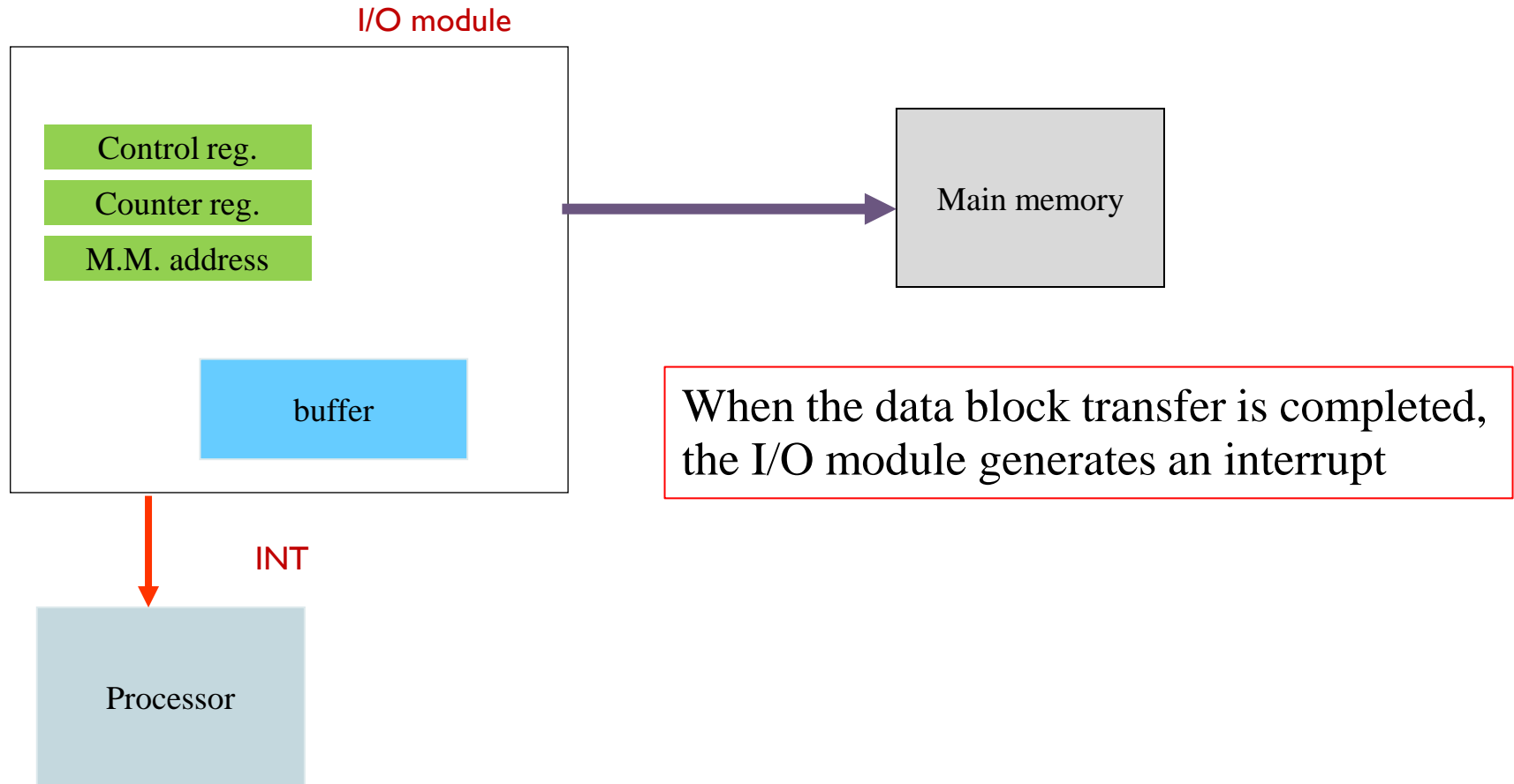
Data transfer with DMA



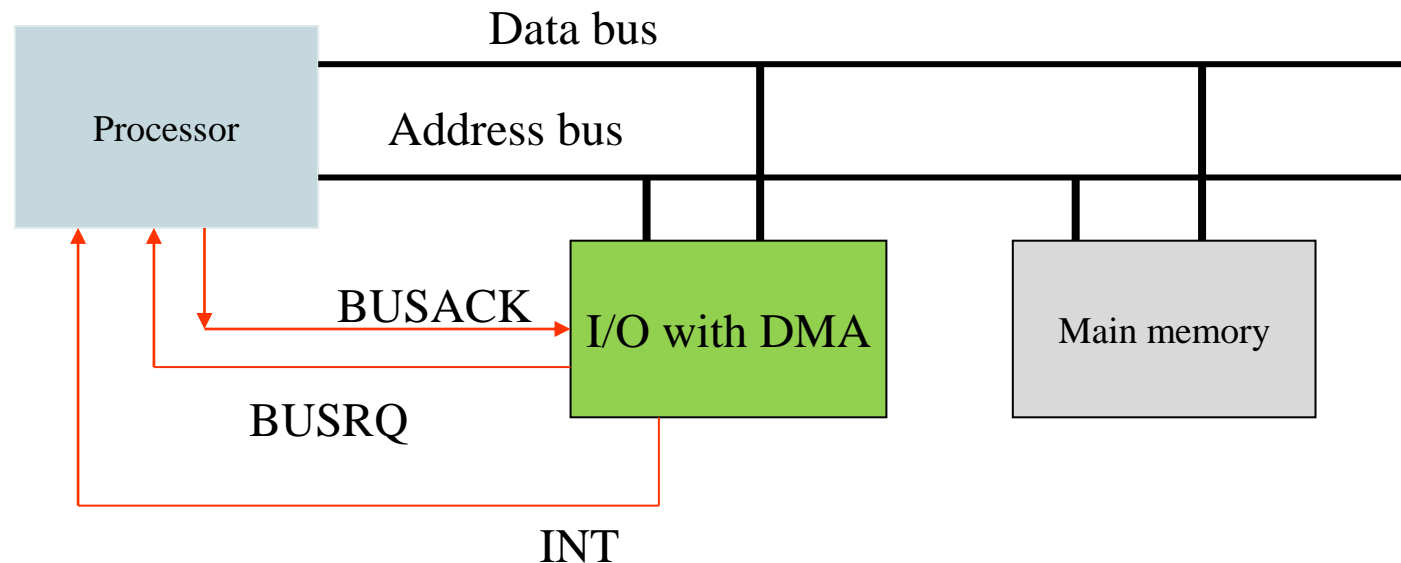
The I/O module transfers the data block:

```
while (counter > 0)
{
    Byte (word) -> MP[MM_address]
    MM_address++
    counter--
}
```

Data transfer with DMA

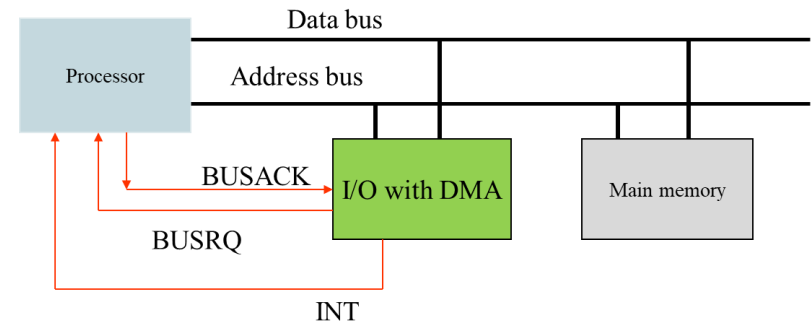


I/O module access to M.M.



- ▶ A coordination is needed to control the access to memory from the processor and I/O modules

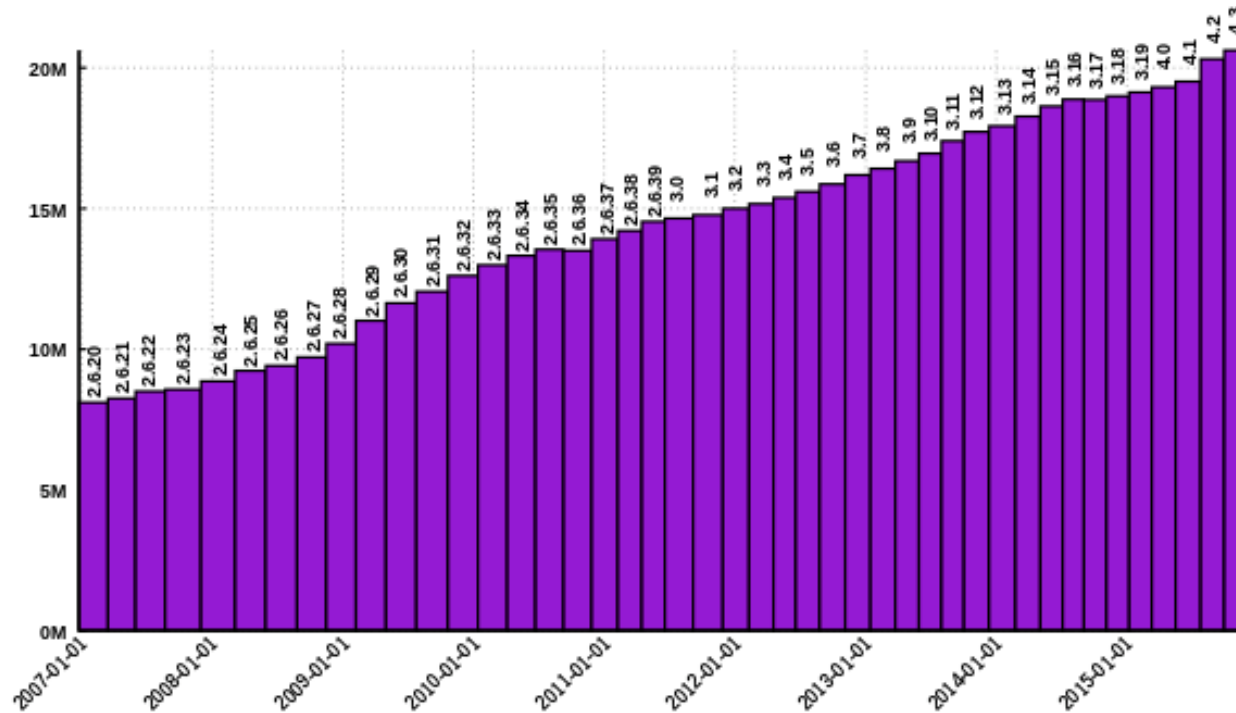
I/O module access to MM: Cycle stealing



- ▶ When the I/O module is ready to transfer a word:
 - ▶ Activates **BUSRQ** signal to request bus access
 - ▶ At the end of each phase of an instruction, the processor checks this signal. If this signal is activated, the processor does not use the buses and activate the **BUSACK** signal
 - ▶ The I/O module access to memory and then deactivate **BUSRQ** signal
 - ▶ The processor then can use the buses
 - ▶ At the end of the data block transfer, the I/O module sends an interrupt signal to the processor.

Curiosity: the importance of drivers

Linux kernel



Lines of code
of the
Linux kernel

- ▶ 70% of Linux code is related to device drivers.

ARCOS Group

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Lesson 6

Input/Output Systems

Computer Structure
Bachelor in Computer Science and Engineering

