

Systems and Networking I

Applied Computer Science and Artificial Intelligence
2025-2026



SAPIENZA
UNIVERSITÀ DI ROMA

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tolomei@di.uniroma1.it

Useful Information

Class schedule

- **Tuesday:** 4 PM – 7 PM
- **Thursday:** 3 PM – 5 PM

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- **website:** <https://github.com/gtolomei/systems-and-networking>
- **moodle:** <https://elearning.uniroma1.it/course/view.php?id=20053>

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Office hours

- Arranged via email
- **in-person** or **remotely**
- **Room 106**, 1st floor Building E
([map](#))

Class Material

- Released on the class website
- Suggested books (though not mandatory!):
 - "*Operating System Concepts*" Ninth Edition – Silberschatz, Galvin, Gagne
 - "*Modern Operating Systems*" Fourth Edition – Tanenbaum, Bos
 - "*Operating Systems: Three Easy Pieces*" – Remzi and Andrea Arpaci-Dusseau [[available online](#)]
- Any additional resource available on the Web!

Moodle

- Provides native support for:
 - Sharing news and messages (forum)
 - Additional class material (e.g., exercises)
 - Exam simulations (e.g., quizzes)
 - ...

Remember to enroll in the course from the
[moodle web page](#)!

Exam

- Moodle Quiz:

- 20 multiple-answer questions (max. 45 minutes)
- Marks: +3 (correct answer), 0 (no answer), -1 (wrong answer)
 - score $\leq 14/30 \rightarrow \text{FAIL}$
 - $15/30 \leq \text{score} \leq 17/30 \rightarrow \text{ORAL REQUIRED}$
 - score $\geq 18/30 \rightarrow \text{PASS}$ (oral upon request by the student)

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- Oral Session:

- Questions and exercises on the subjects covered during the whole semester

Outline of the Course

- Part I: Introduction

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- Part VI: File System
- Part VII: Advanced Topics(?)

Part I: Introduction

Language and Naming Conventions

- OS → Operating System
- HW → Hardware
- SW → Software
- VM → Virtual Machine
- ...
- Other shortcuts/acronyms may appear here and there without notice! Please, ask if anything is not clear!

What is an Operating System?

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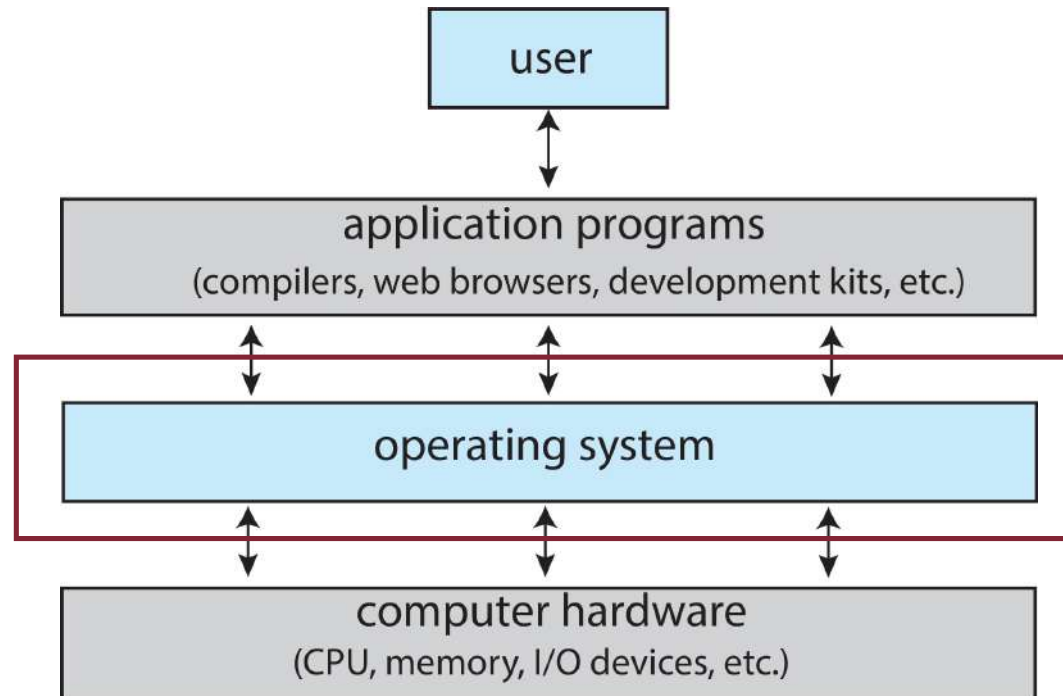
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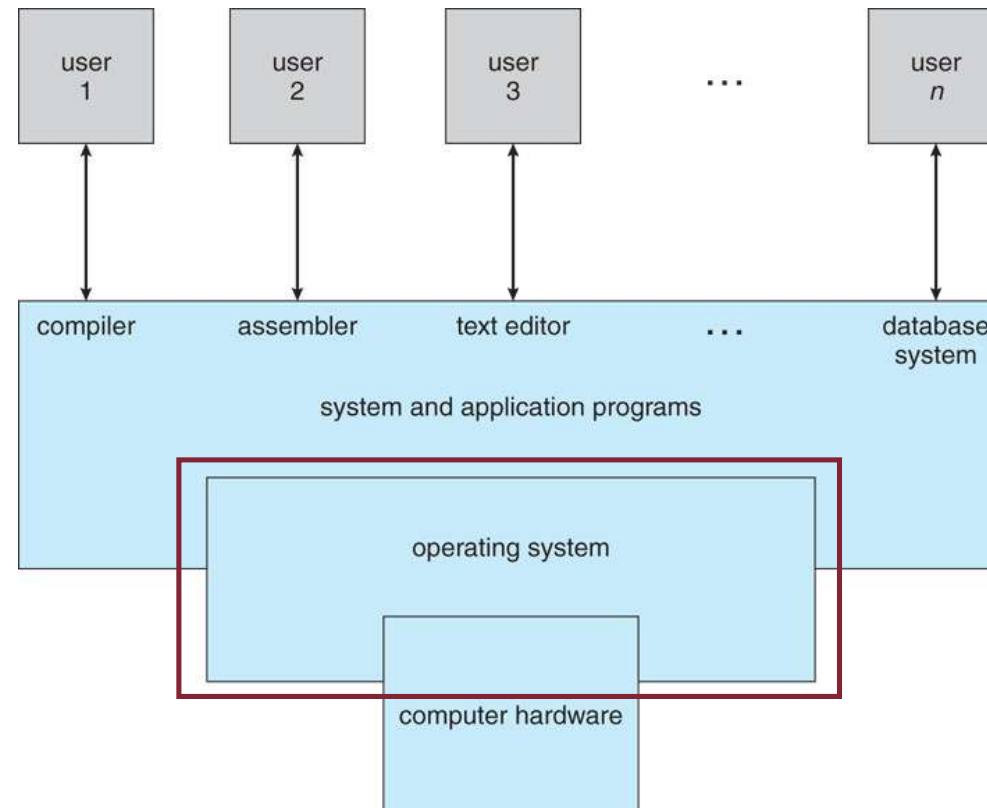
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- However, the definition below is quite appropriate:

Implementation of a virtual machine that is (hopefully) easier to program than bare hardware

Computer System Overview



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- It is a **system design** choice to decide what to include in the OS
- Different systems may have different requirements:
 - general-purpose, real-time, mobile, etc.
- Typically, we distinguish between:
 - **kernel** → the "core" of the OS (always up and running)
 - **system programs** → everything else which is still part of the OS

OS Wears Many Hats

- Referee (Resource Manager)
 - Manages shared physical resources: CPUs, memory, I/O, etc.



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 - To achieve **fairness** and **efficiency**



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 - To give applications/users the **illusion of infinite resources** available



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- Glue (HW/SW Interface)
 - Provides a set of **common services** (APIs) to separate HW from SW



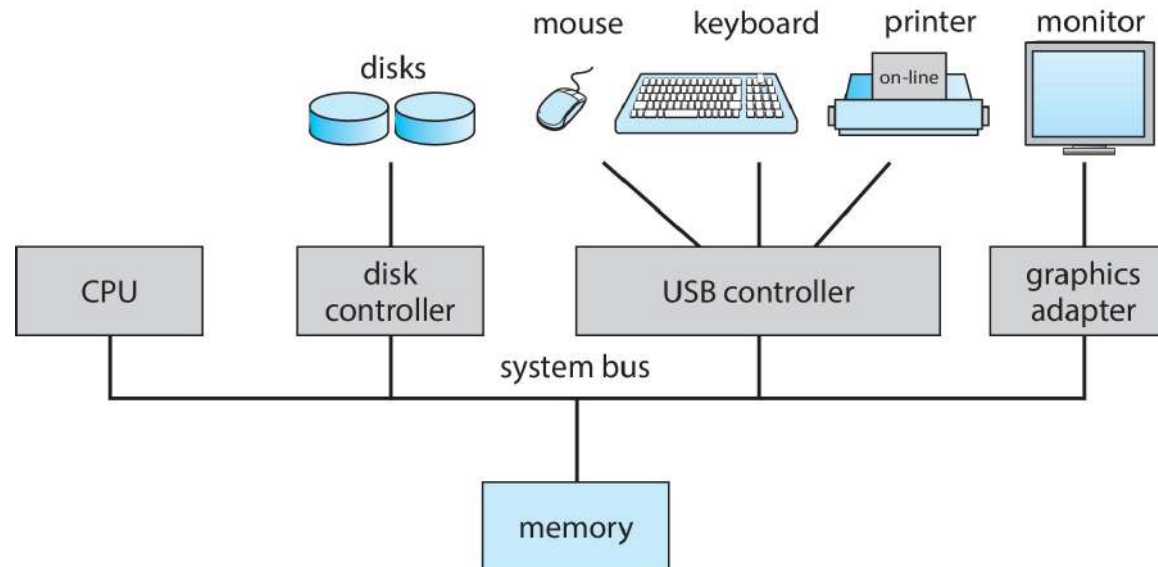
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- Glue (HW/SW Interface)
 - Provides a set of **common services** (APIs) to separate HW from SW
 - To allow applications/users to interact with the system **without talking directly to the HW**

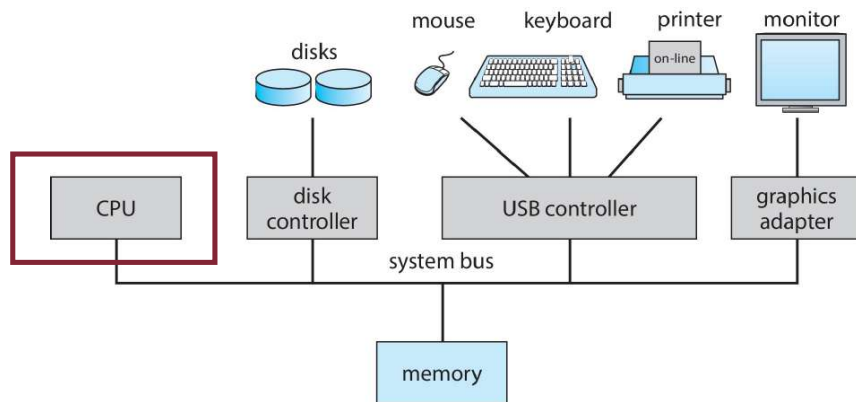


Computer System Organization

High-Level View of a Computer



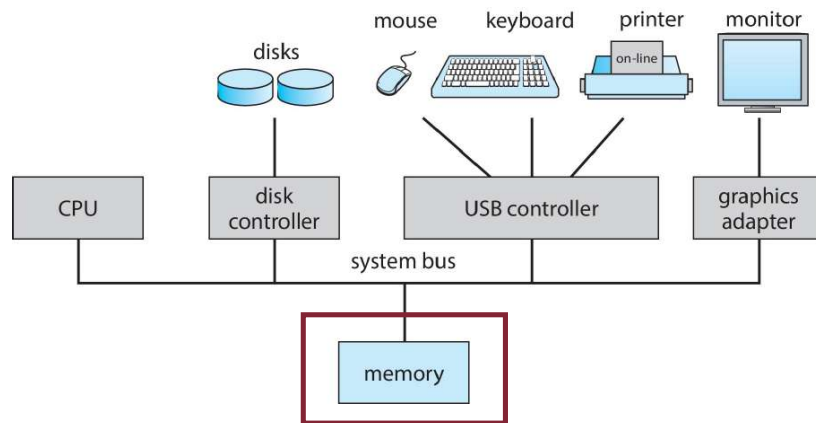
High-Level View of a Computer



CPU

- The processor that performs the actual computation
- Multiple cores are now common in modern architectures

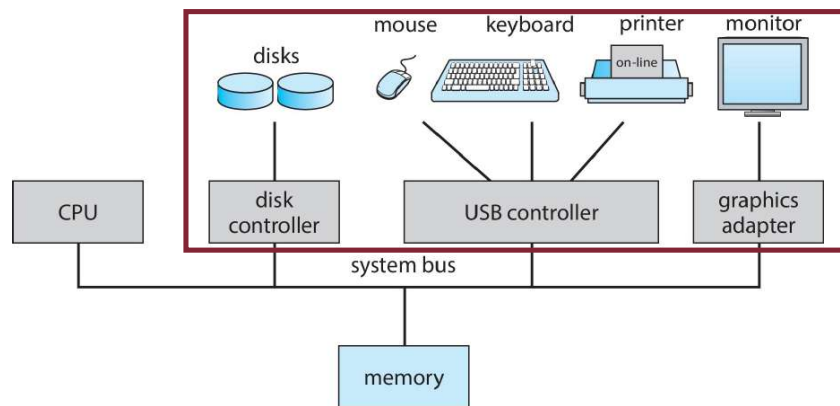
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Main Memory

- Stores data and instructions used by the CPU
- Shared between CPU and I/O

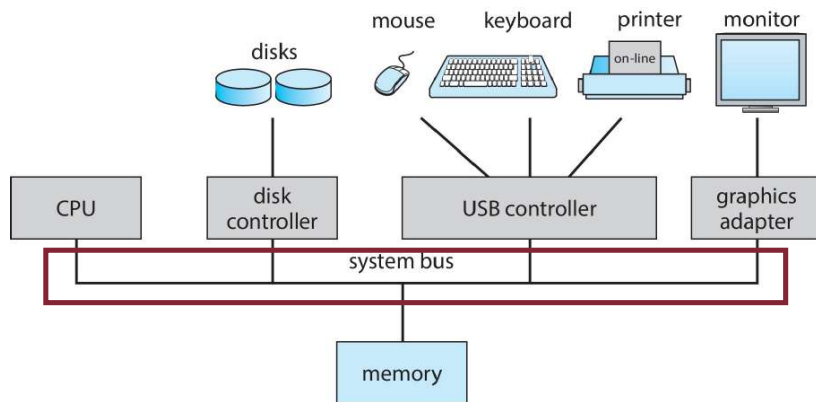
High-Level View of a Computer



I/O devices

- terminal, keyboard, disks, etc.
- Associated with specific device controllers

High-Level View of a Computer



System Bus

- Communication medium between CPU, memory, and peripherals

Computer Architecture Model

- Conceptually, the same architectural model for many computing devices:
 - PCs/laptops
 - High-end servers
 - Smartphones/Tablets
 - etc.

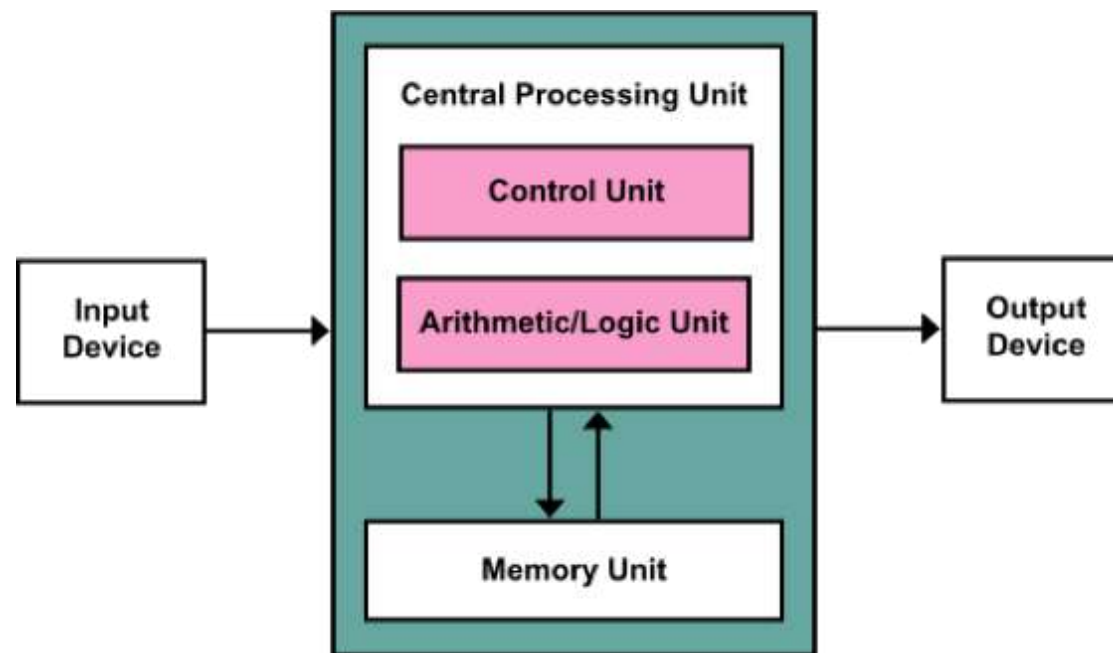
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- Based on **stored-program** concept (as opposed to fixed-program)

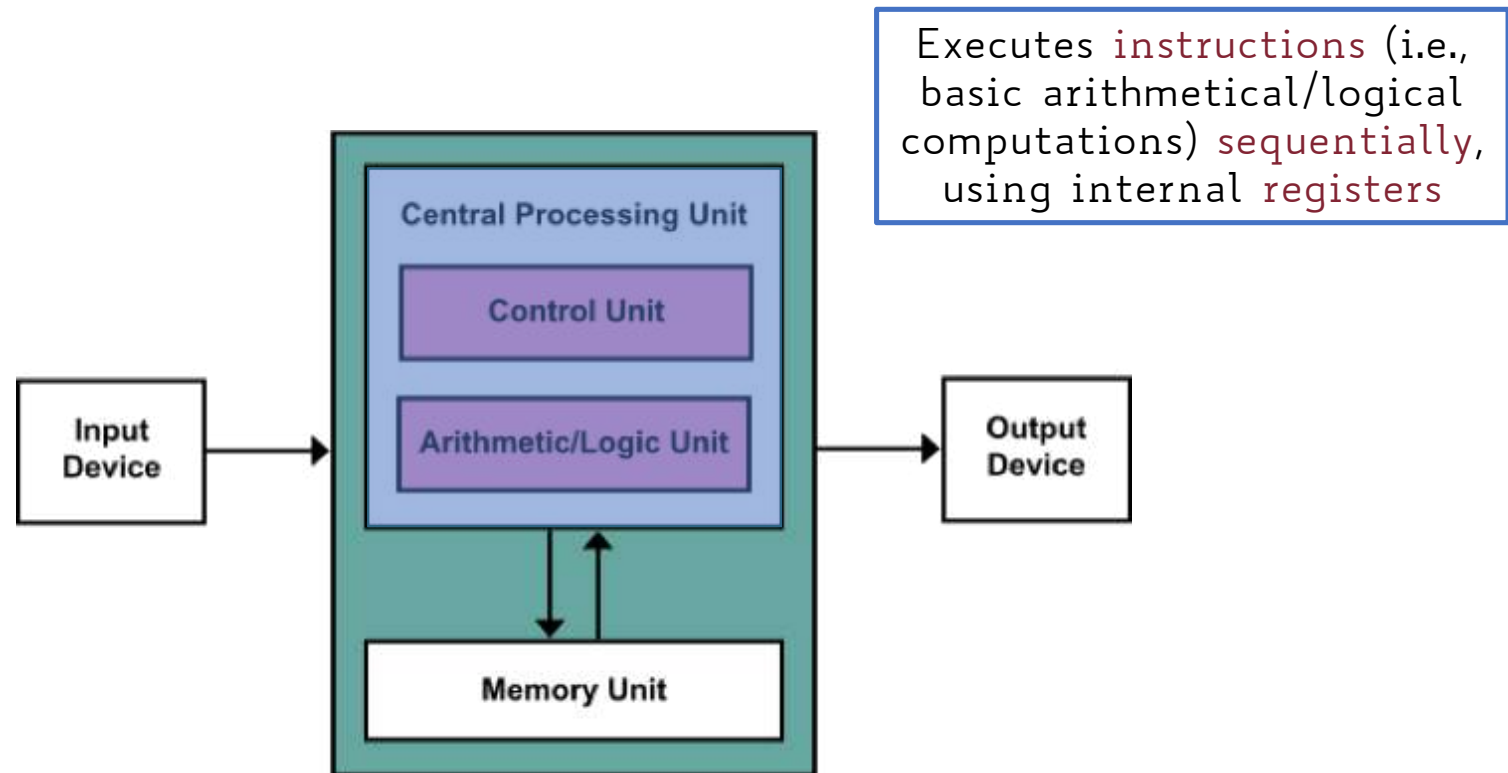


John von Neumann

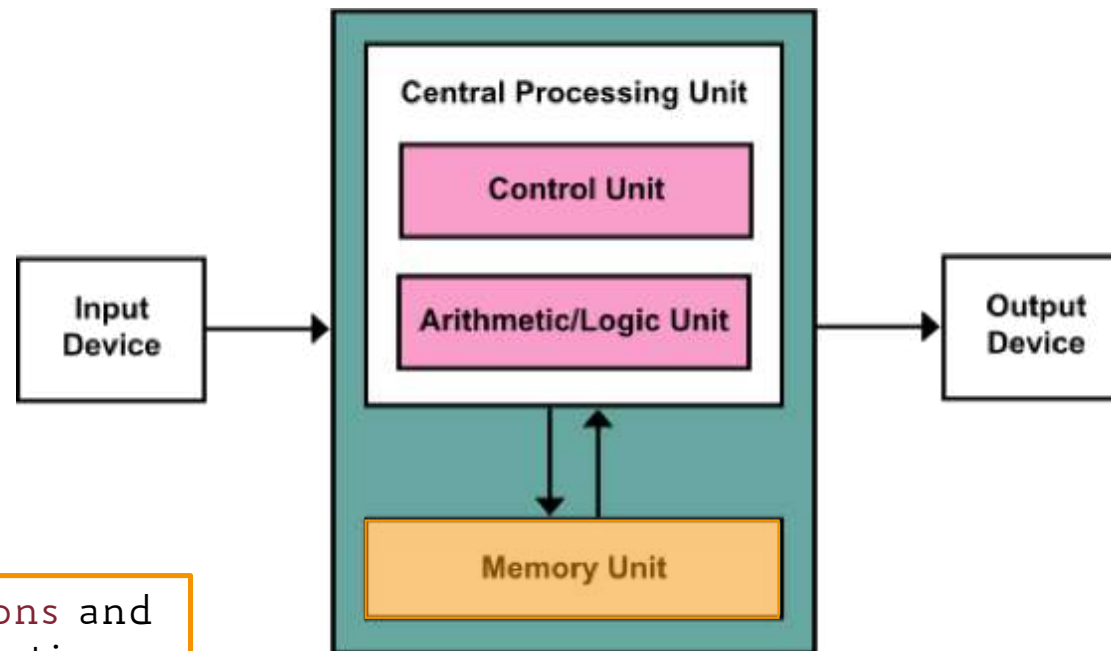
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Contains **instructions** and **data** (which instructions operate on)

Central Processing Unit (CPU)

Instruction Cycle

- The CPU performs the following 5 stages cyclically:

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DECODE

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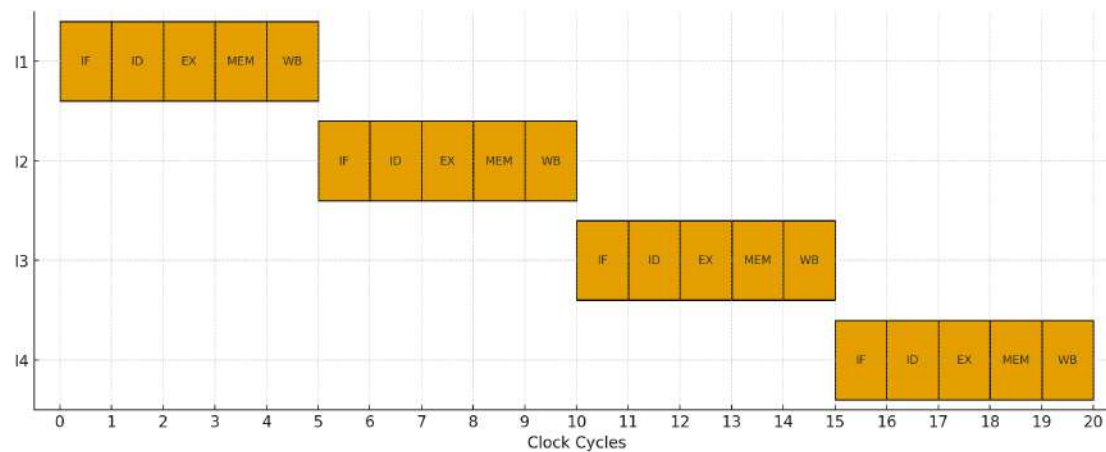
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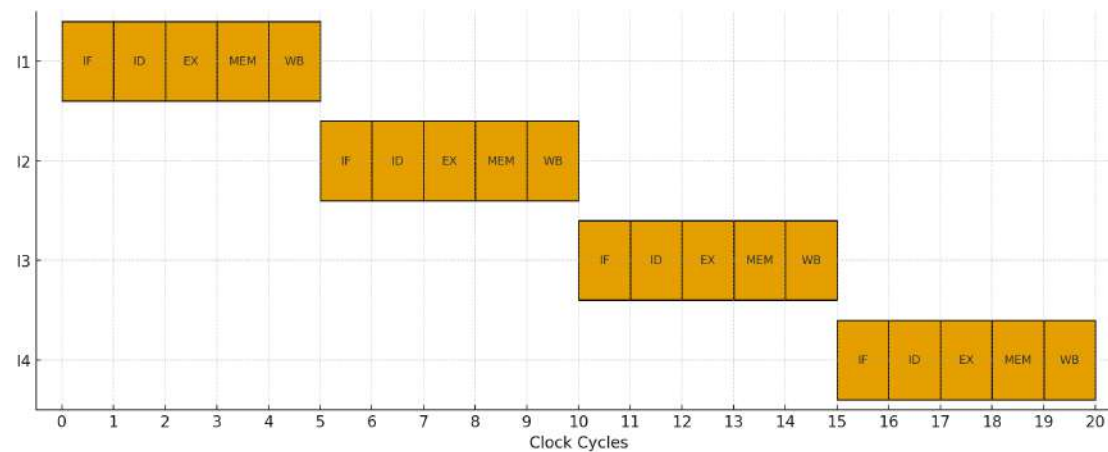
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4 instructions: I1,... I4



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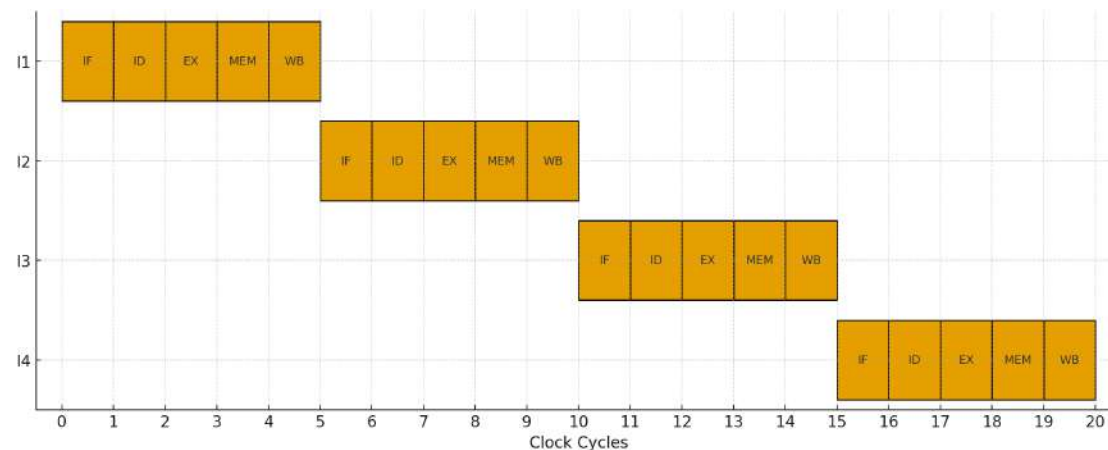


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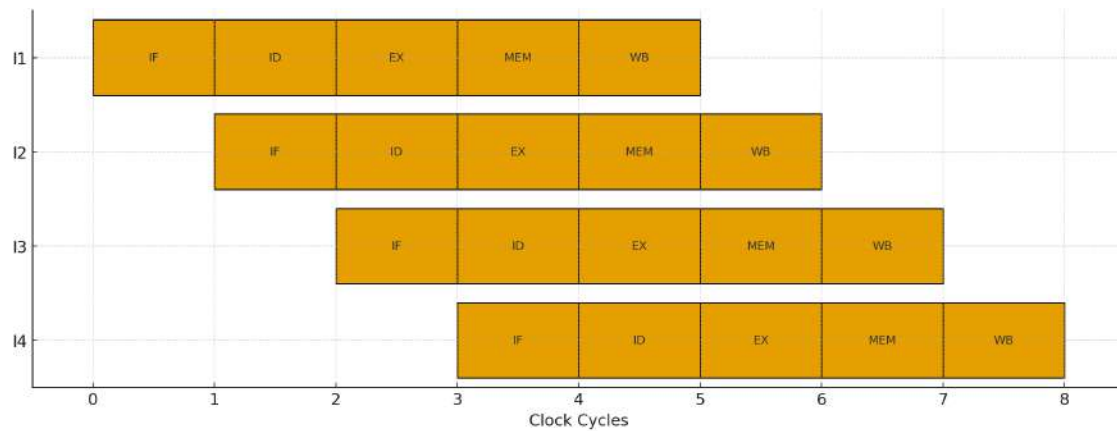
Assumption:

Each stage takes one clock cycle
(may not always be the case!)

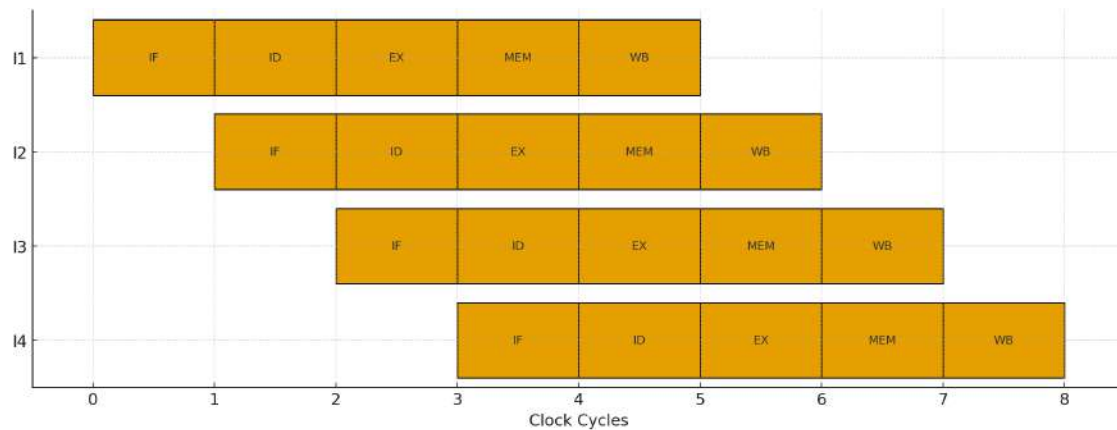
**5 Cycles per Instruction
(CPI)**

Instruction Cycle: Pipelined

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Instruction Cycle: Pipelined

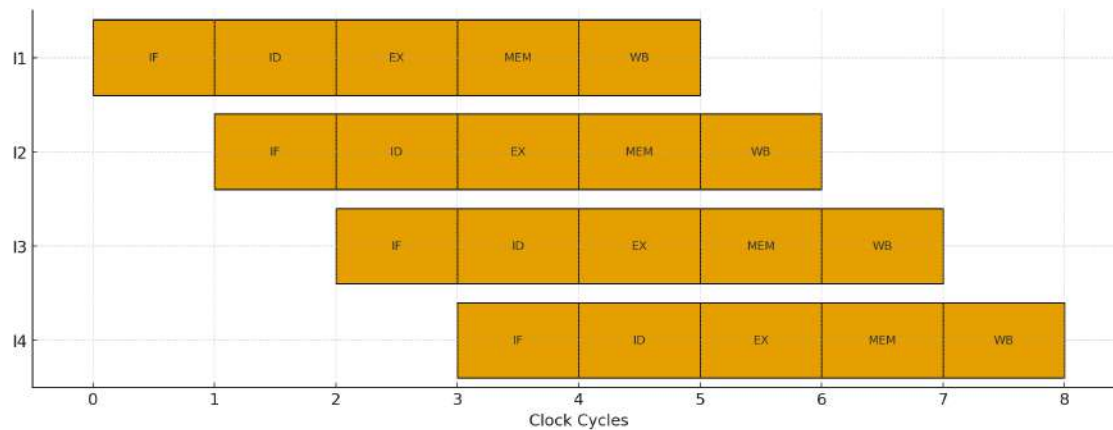


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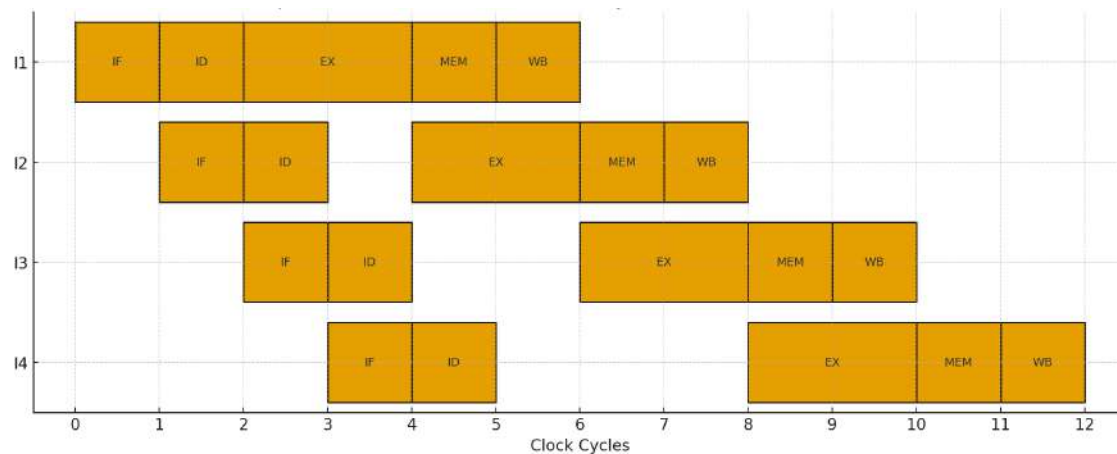
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(may not always be the case!)

**1 Cycle per Instruction
(CPI)
on average**

Instruction Cycle: Pipelined (v.2)



4 instructions: I1,... I4

Each stage runs **in parallel** whenever possible or **wait**

Each stage may take more than one clock cycle
(e.g., EX takes two!)

**2 Cycles per Instruction (CPI)
on average**

Machine Language

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 - A single bit is the smallest unit of (digital) information
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- A **word** is the unit of data the CPU can directly operate on
 - today ranging from 32 to 64 bits

A Side Note on Units

Prefixes for multiples of bits (bit) or bytes (B)					
Decimal			Binary		
Value		SI	Value	IEC	JEDEC
1000	10^3	k kilo	1024	2^{10} Ki kibi	K kilo
1000^2	10^6	M mega	1024^2	2^{20} Mi mebi	M mega
1000^3	10^9	G giga	1024^3	2^{30} Gi gibi	G giga
1000^4	10^{12}	T tera	1024^4	2^{40} Ti tebi	–
1000^5	10^{15}	P peta	1024^5	2^{50} Pi pebi	–
1000^6	10^{18}	E exa	1024^6	2^{60} Ei exbi	–
1000^7	10^{21}	Z zetta	1024^7	2^{70} Zi zebi	–
1000^8	10^{24}	Y yotta	1024^8	2^{80} Yi yobi	–

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- An **abstraction** of the underlying physical (hardware) architecture (e.g., x86, ARM, SPARC, MIPS, etc.)

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- Special-purpose (x86):
 - `esp` → Stack pointer for top address of the stack
 - `ebp` → Stack base pointer for the address of the current stack frame
 - `eip` → Instruction pointer, holds the program counter (i.e., the address of next instruction)

Single- vs. Multi-Processor

Single-Processor Systems

- One main CPU for executing programs
- Other dedicated processors that do not run programs (e.g., disk controllers, GPUs, etc.)

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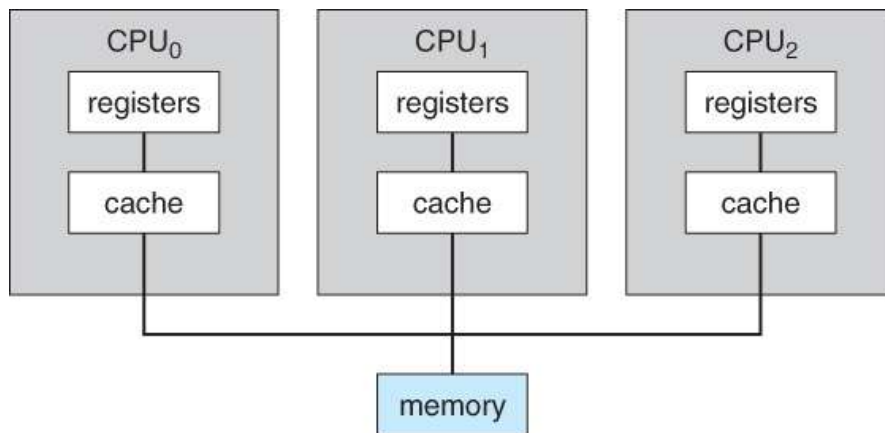
Our main focus!

Multi-Processor Systems

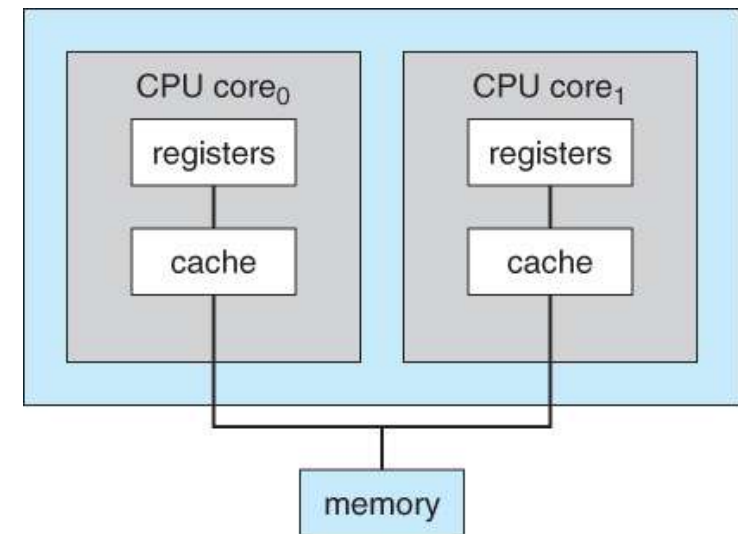
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Multi-Processor Systems: Examples

Symmetric Multiprocessing Architecture

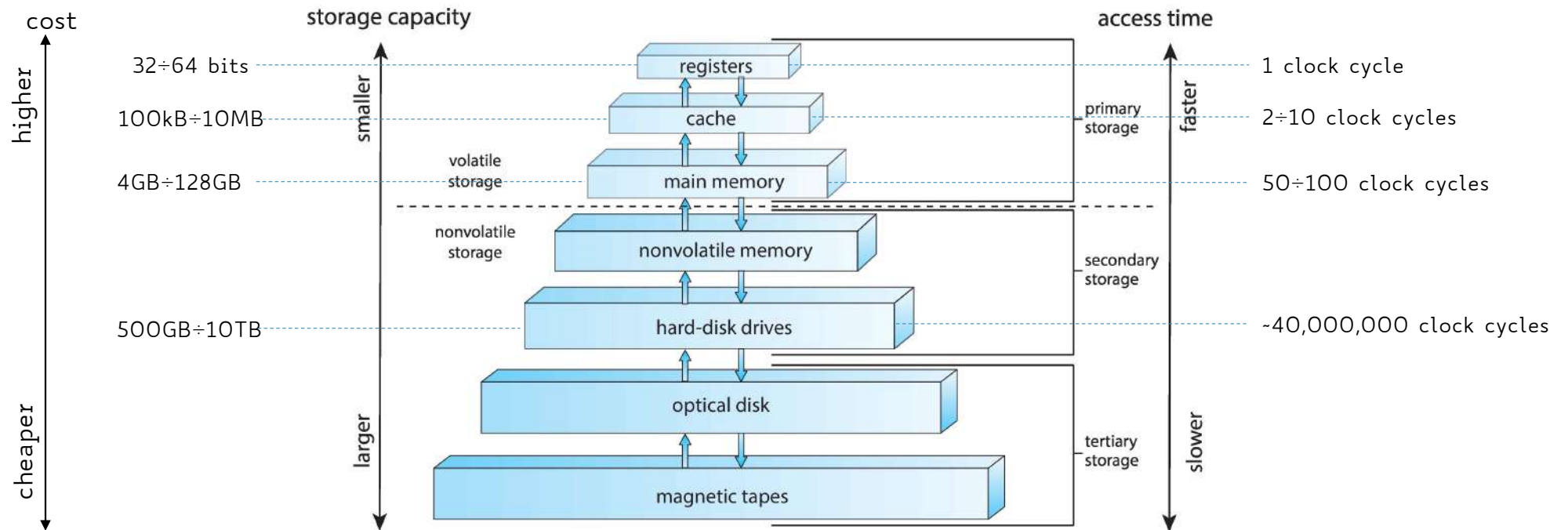


Multicore Architecture

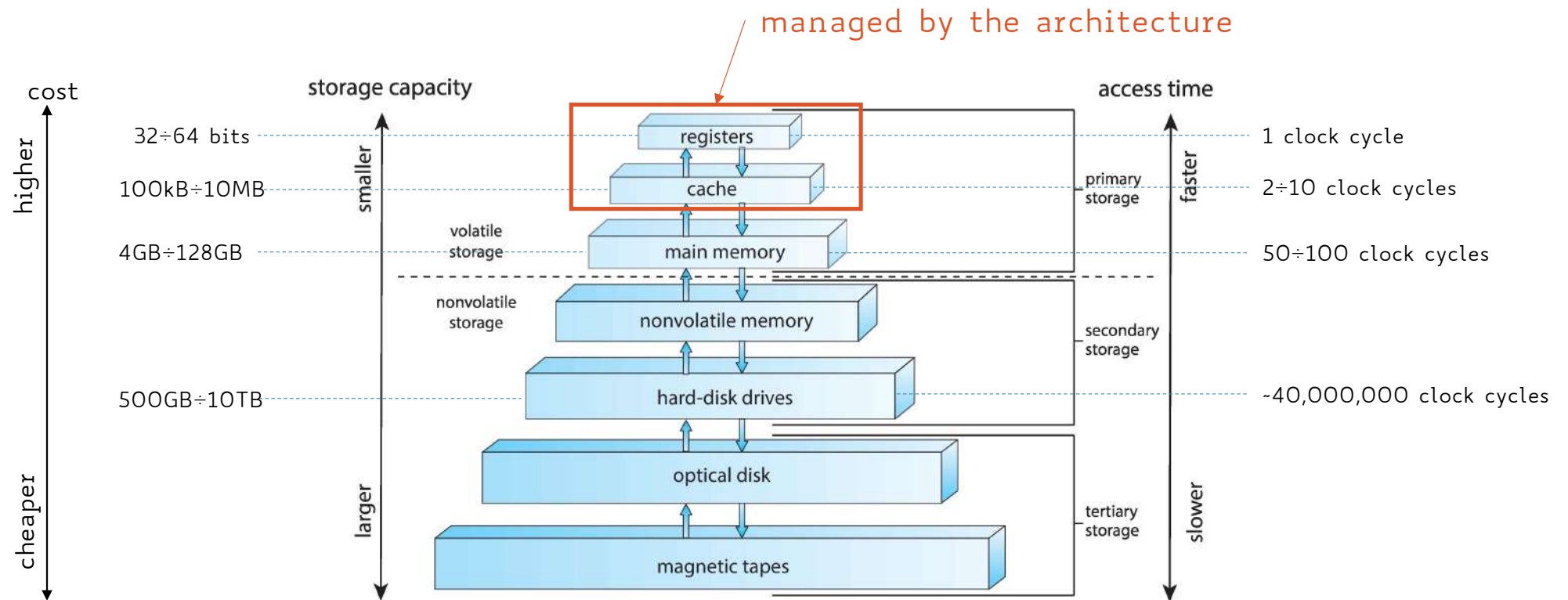


Memory

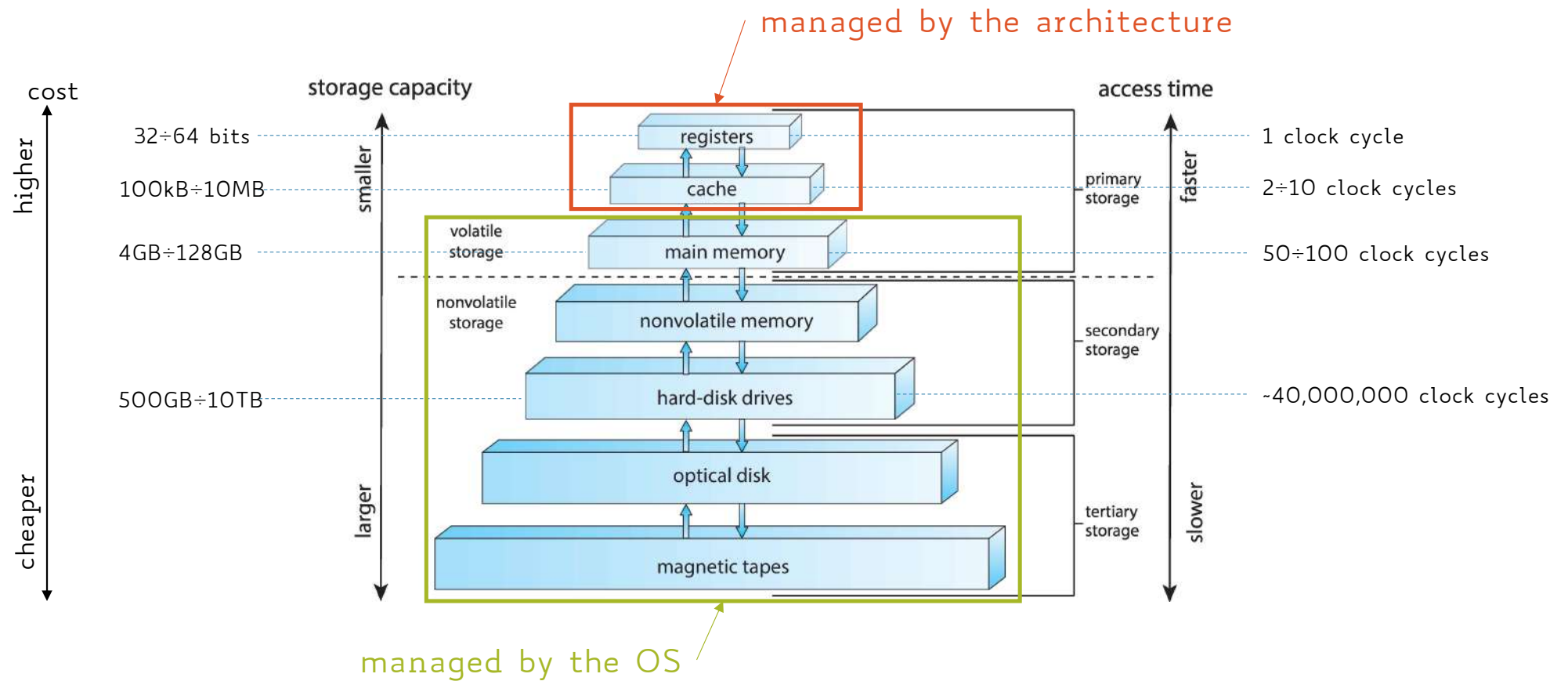
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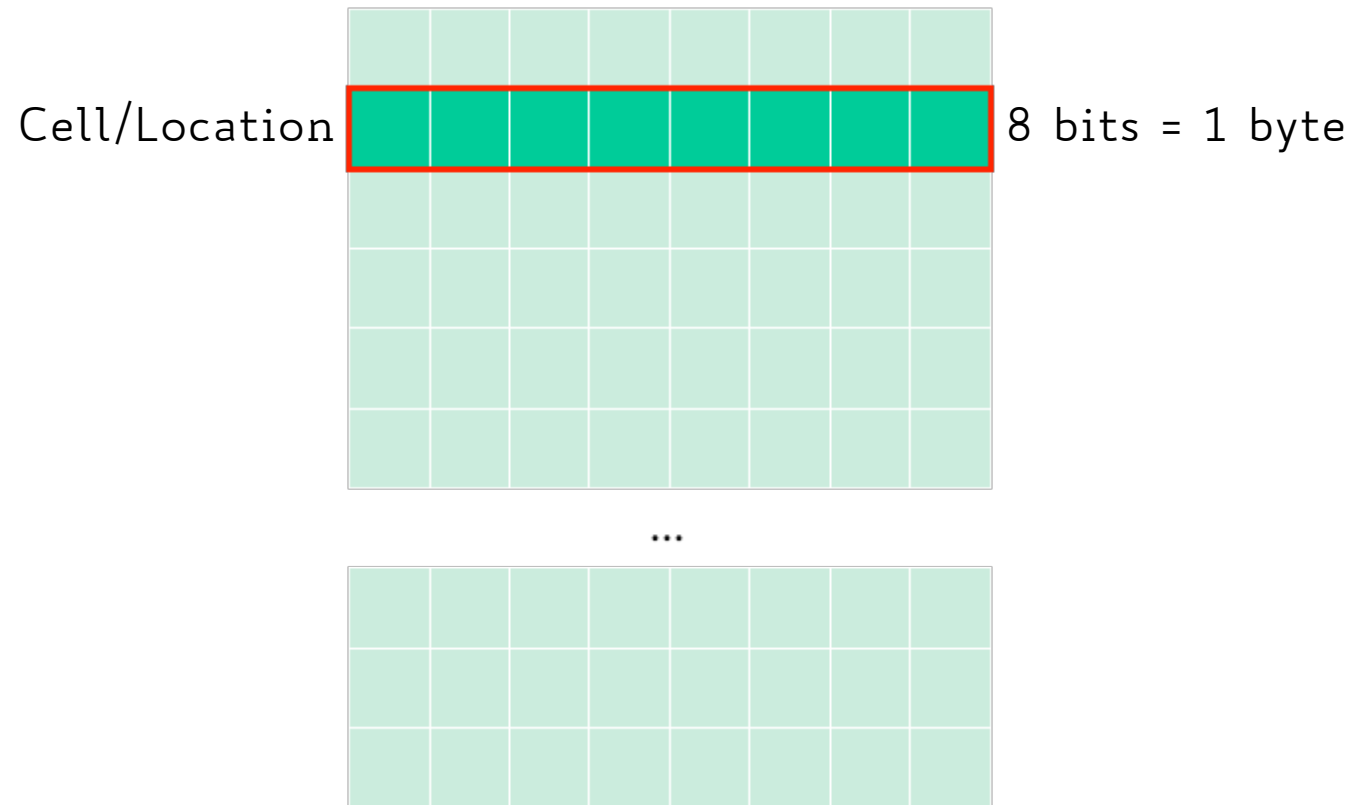
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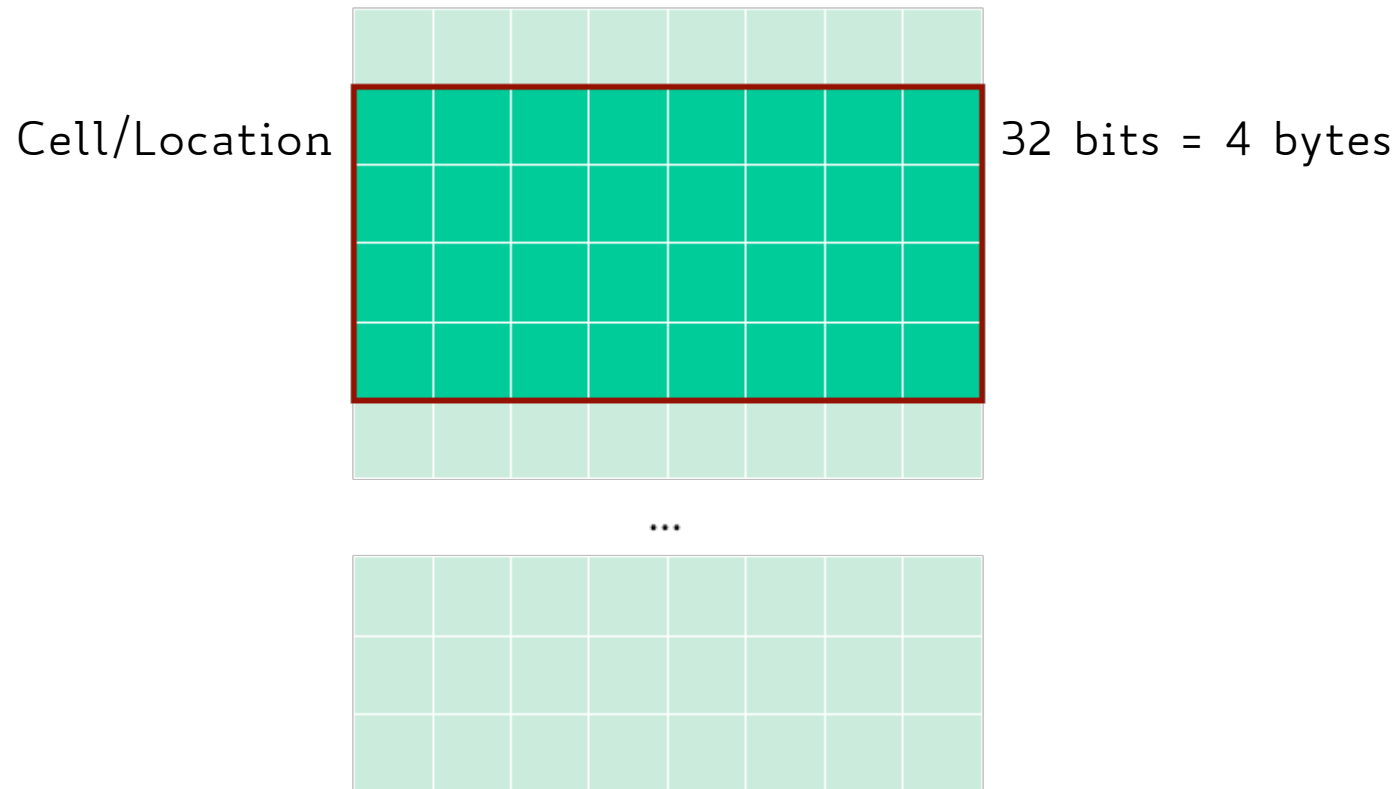
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- The smallest addressable unit is usually 1 byte

Memory Cell (1)



Memory Cell (2)



Memory Address (Single Byte)

00000000							
00000001							
00000010							
00000011							
00000100							
00000101							
...							
00100010							
00100011							
00100100							

Computer Buses

System Bus

- Initially, a single bus to handle all the traffic

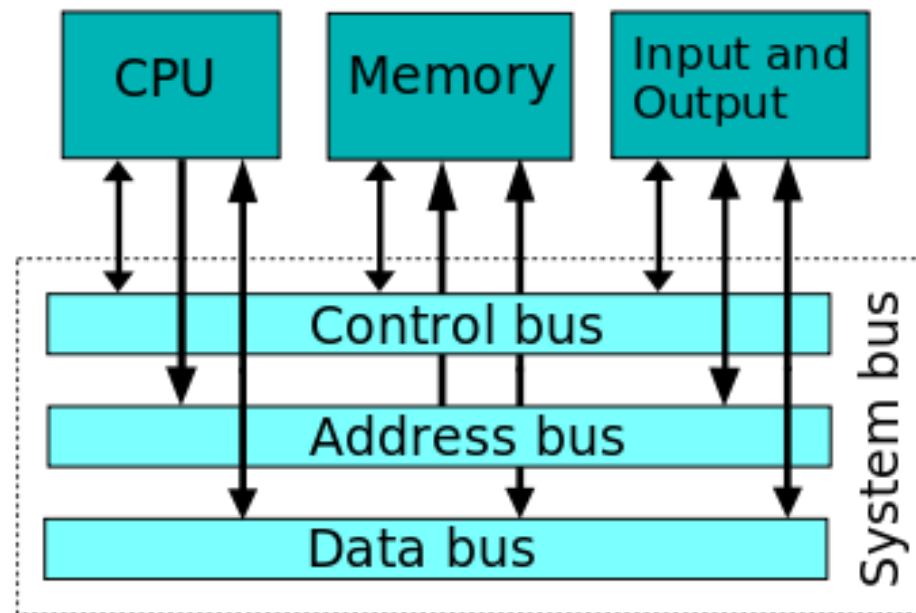
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- More dedicated buses have been added to manage CPU-to-memory and I/O traffic
 - PCI, SATA, USB, etc.

System Bus



I/O Devices

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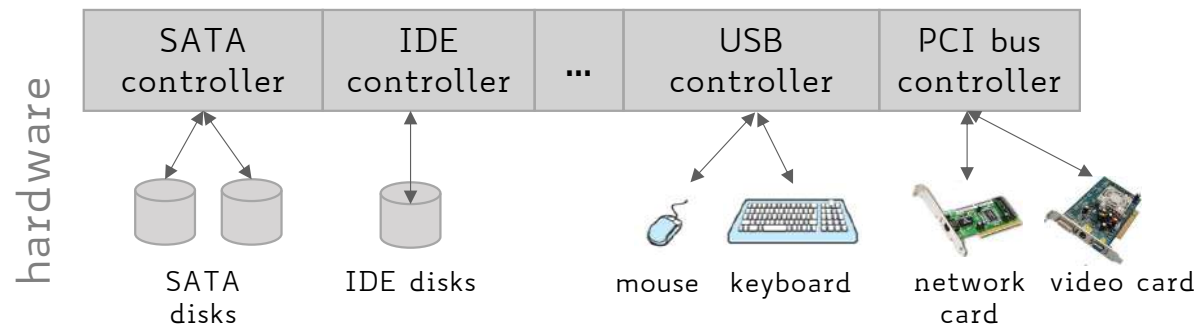
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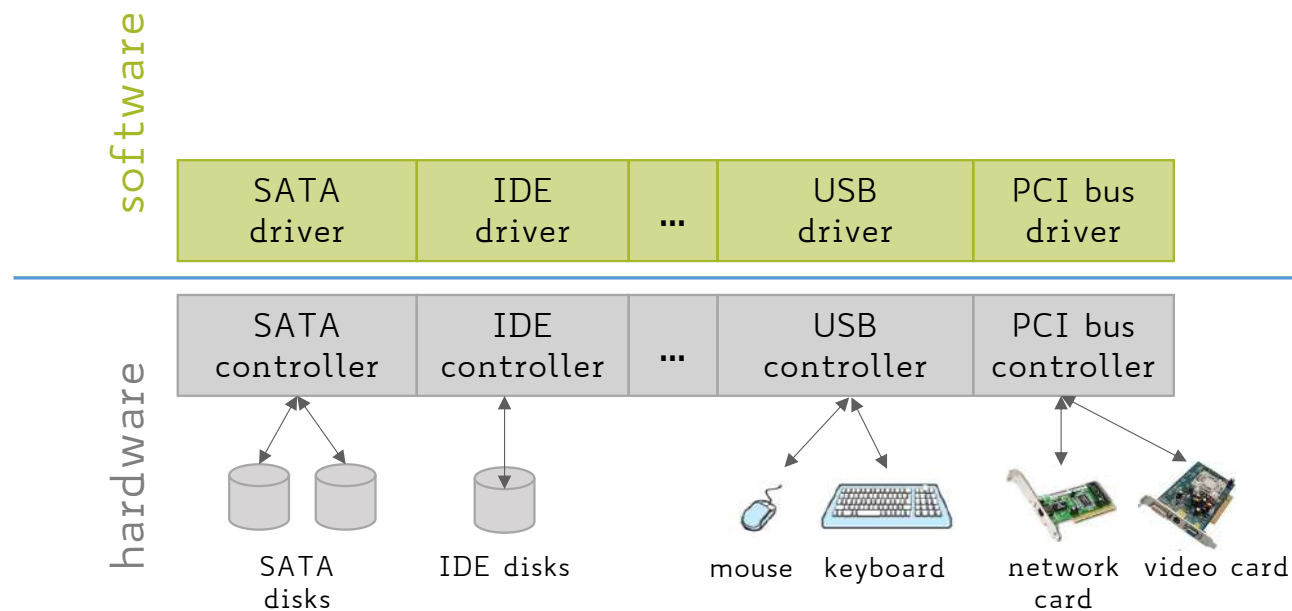
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- OS talks to a device controller using a specific **device driver**

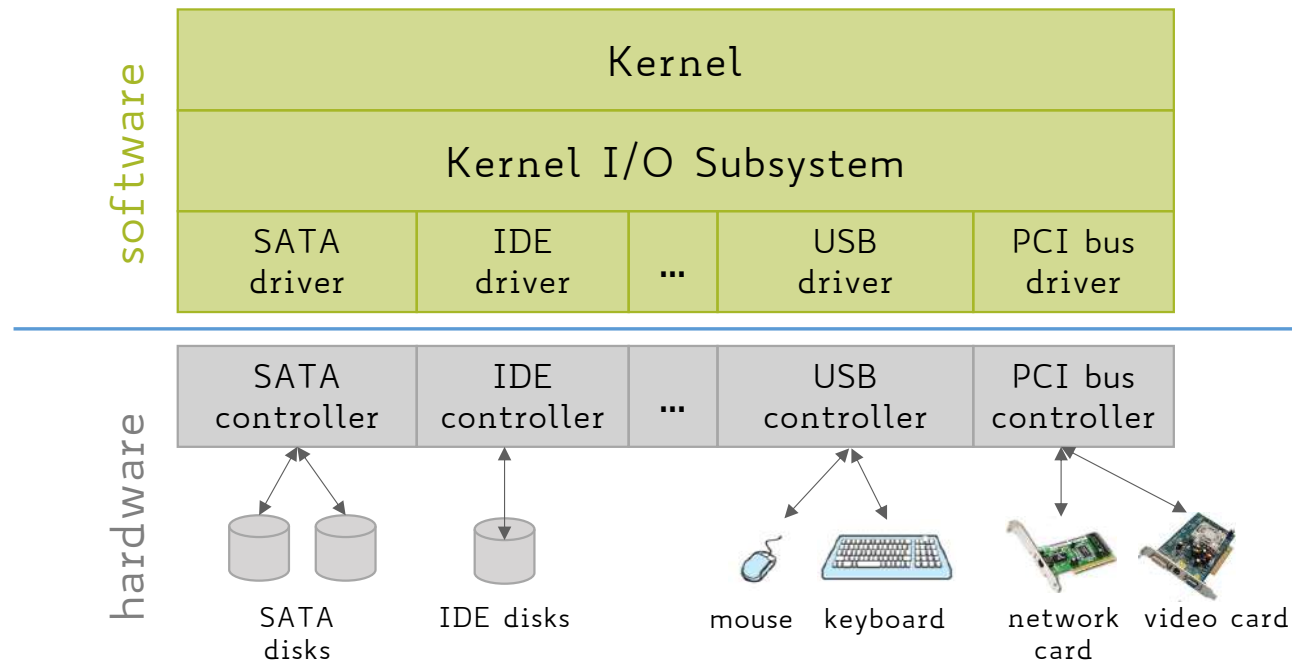
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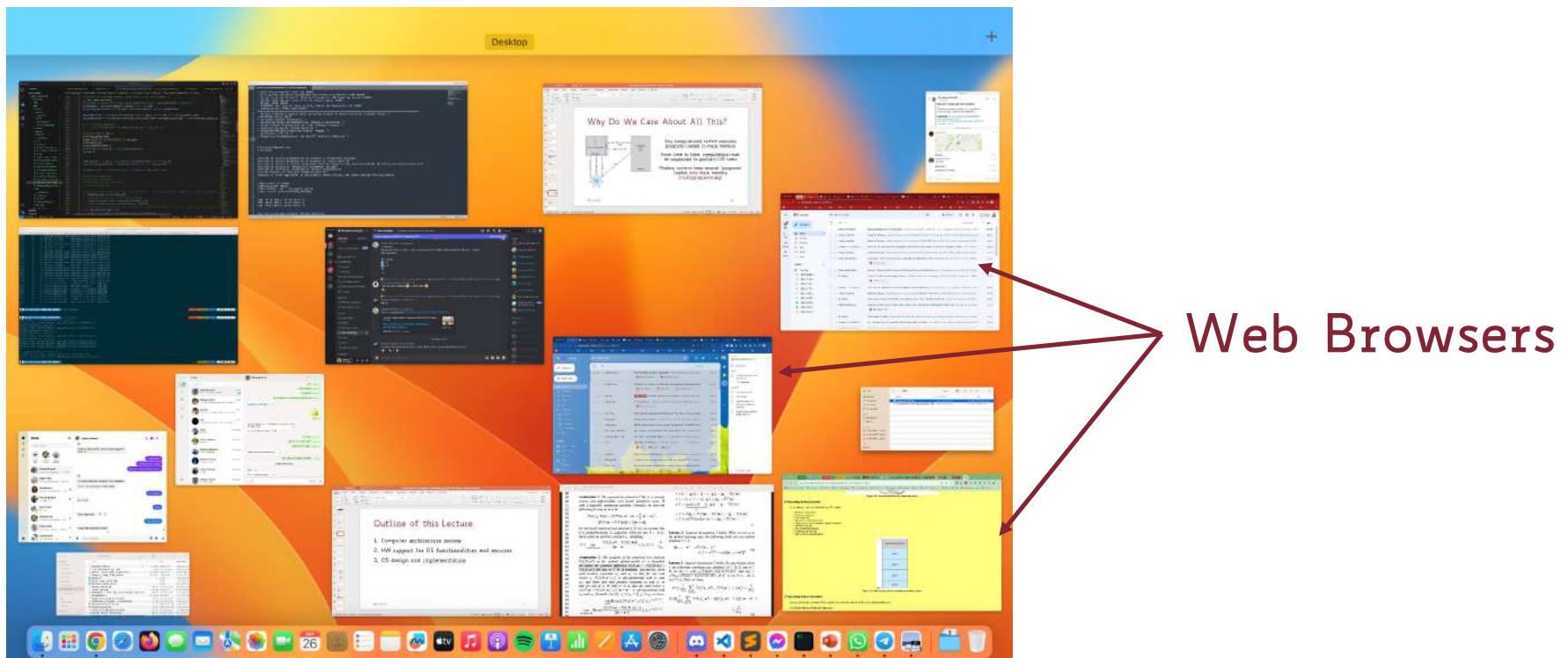
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 - **Configuration/Control registers** → used by the CPU to configure and control the device

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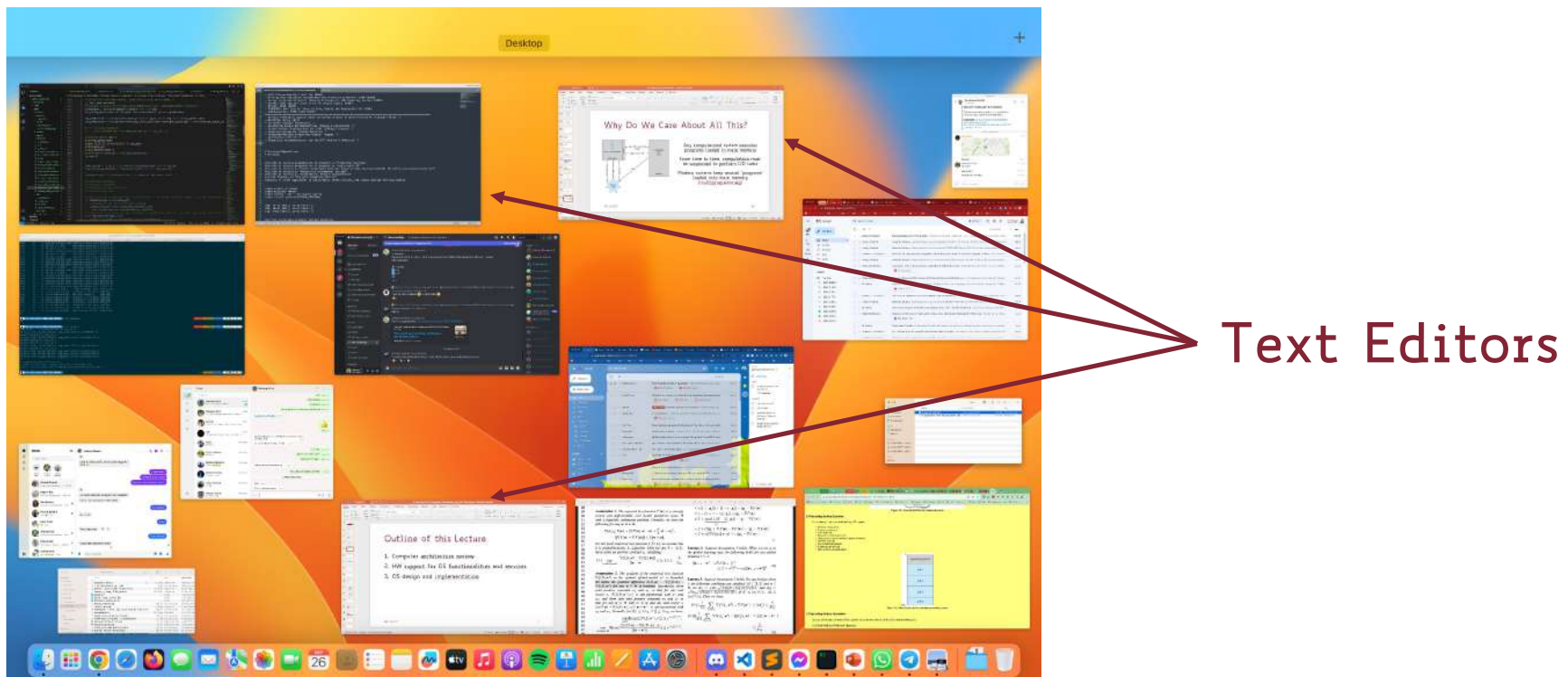
- Every device controller has a number of dedicated registers to communicate with it:
 - **Status registers** → provide status information to the CPU about the I/O device (e.g., idle, ready for input, busy, error, transaction complete)
 - **Configuration/Control registers** → used by the CPU to configure and control the device
 - **Data registers** → used to read data from or send data to the I/O device

Modern Computer Systems

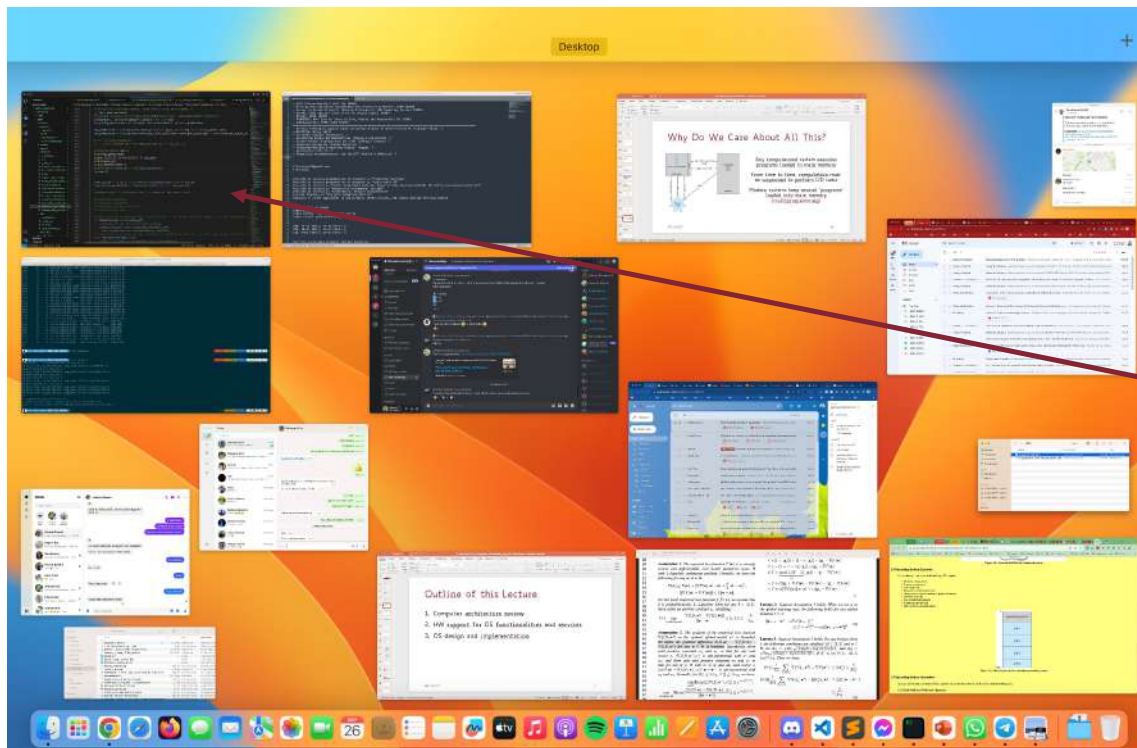
Many User Applications Running



Many User Applications Running

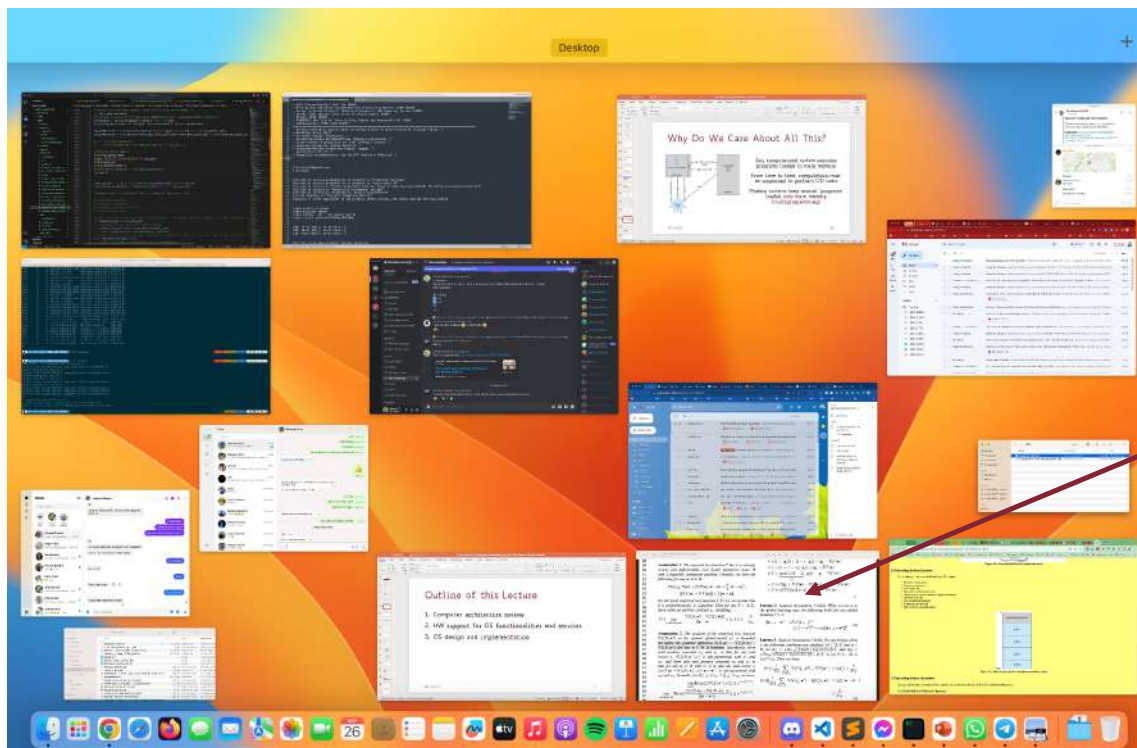


Many User Applications Running



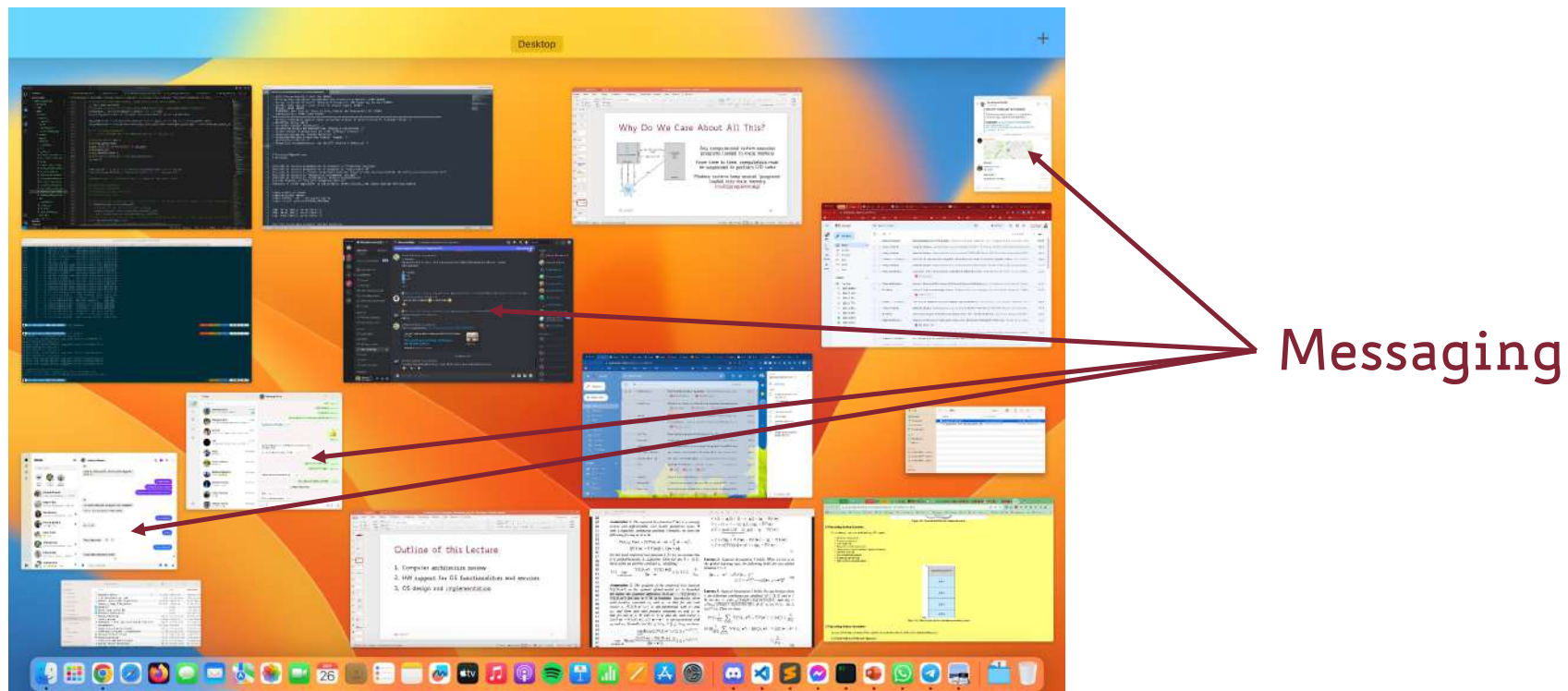
IDE
(code development)

Many User Applications Running

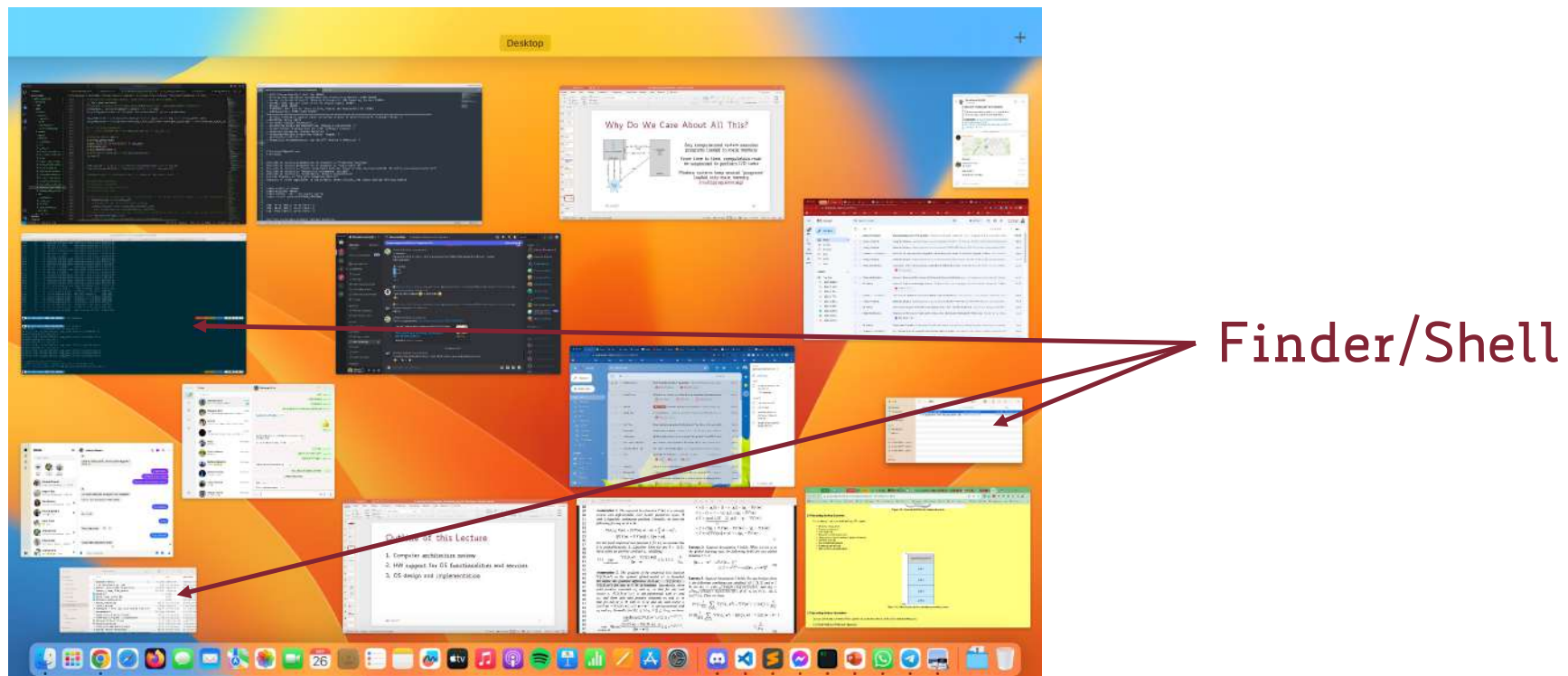


PDF Viewer

Many User Applications Running



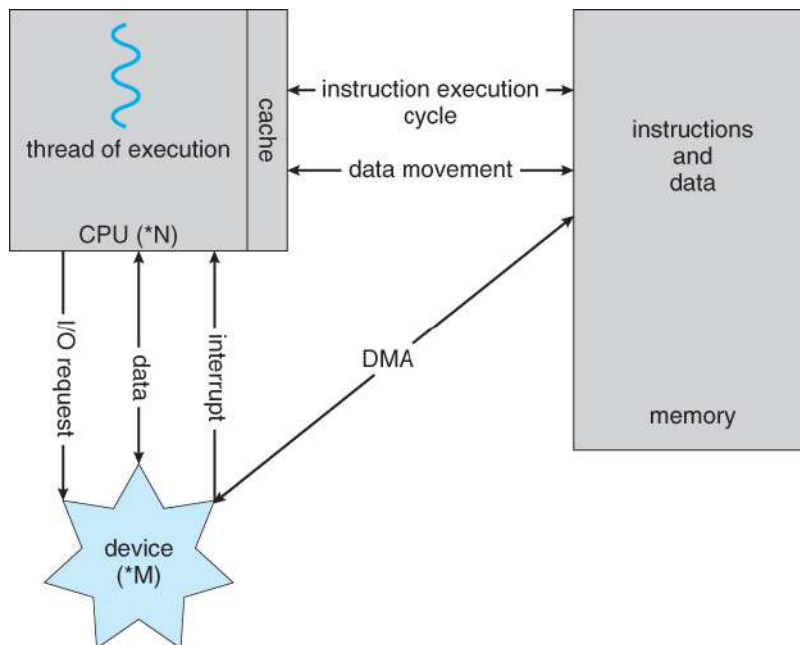
Many System Programs Running



Not Just Laptops/PCs...



Why Do We Care About All This?

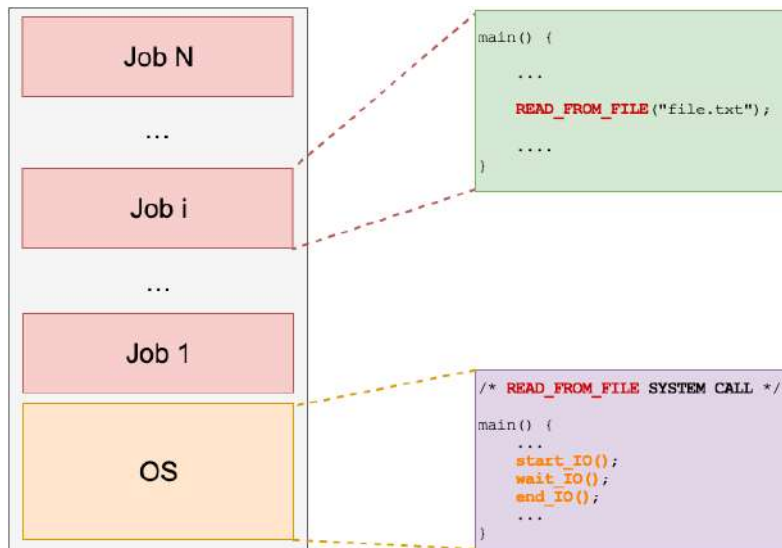


Any computerized system executes programs loaded in main memory

From time to time, computation must be suspended to perform I/O tasks

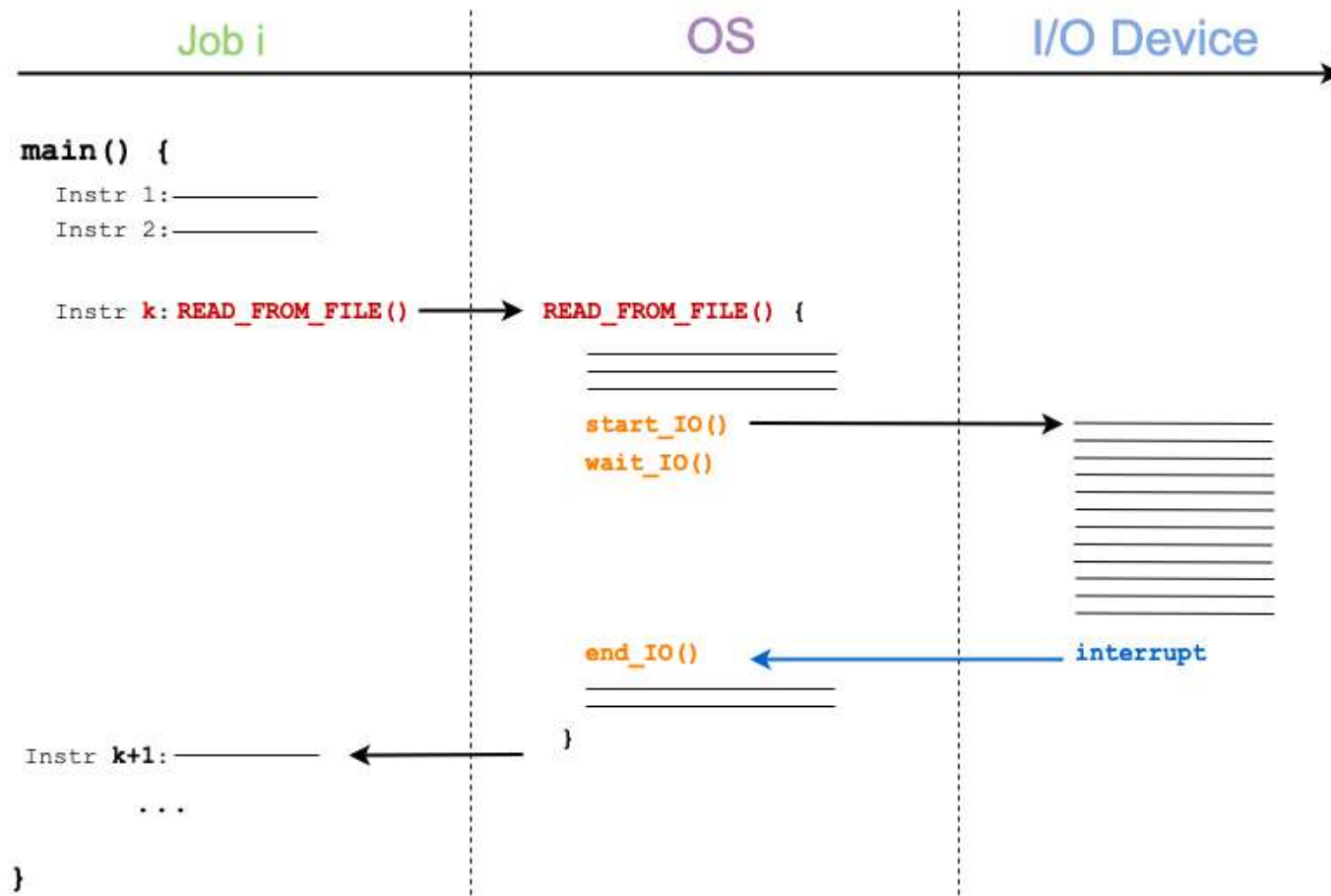
Modern systems keep several "programs" loaded into main memory
(**multiprogramming**)

Multiprogramming Systems (1960s)

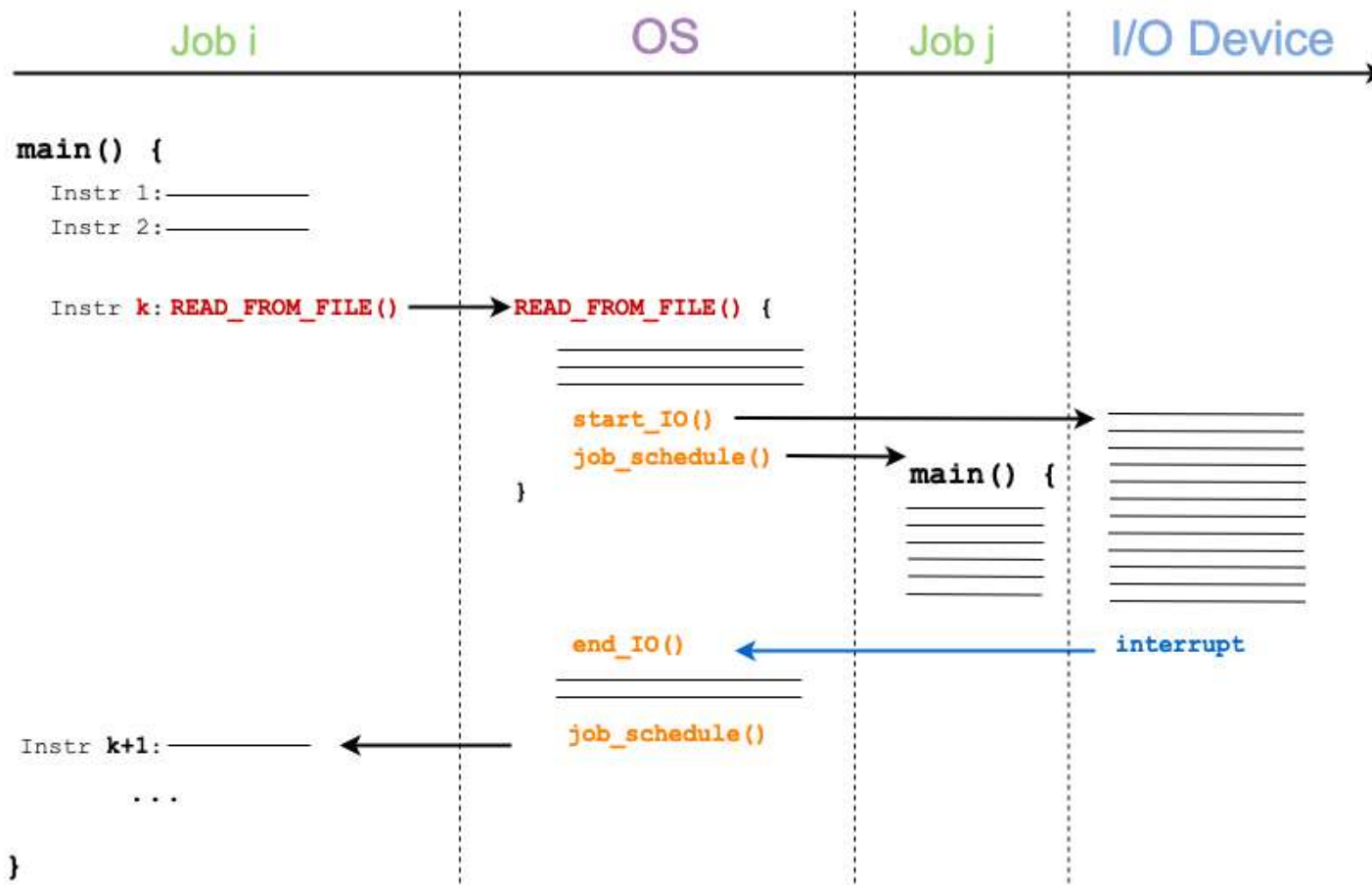


- Keep several jobs loaded in memory
- Multiplex CPU between jobs
- OS responsibilities:
 - job scheduling
 - memory protection
 - I/O operations
- **Problem:** CPU is left **idle** while **blocking** I/O operations take place

Blocking System I/O



Non-Blocking System I/O

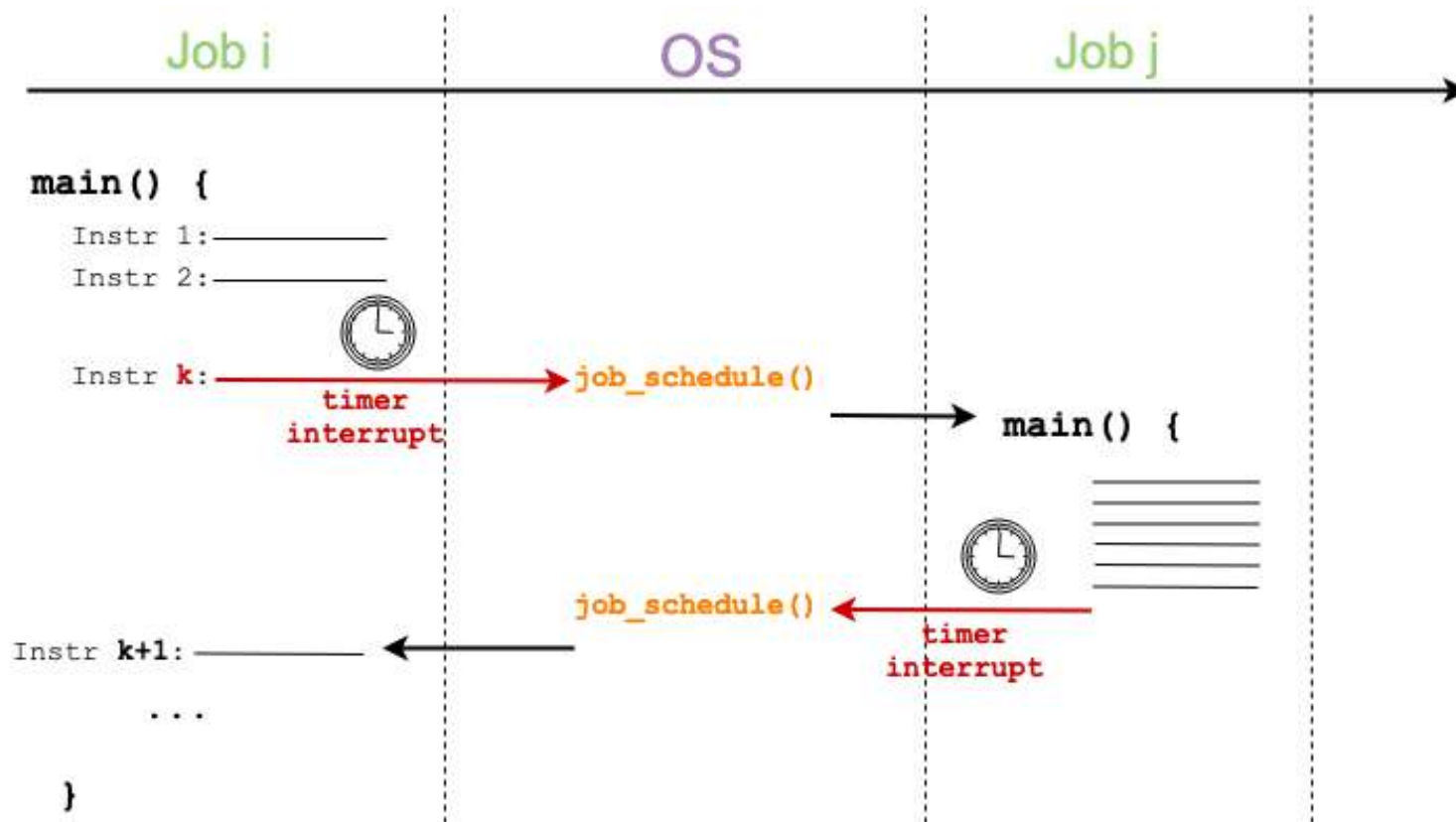


Time-sharing Systems (1970s)



- Many users connected to the same CPU via cheap consoles
- Timer interrupt used to multiplex CPU between jobs
- Illusion of parallelism (pseudo-parallelism)
- Ken Thompson & Dennis Ritchie → **UNIX OS**

Pseudo-parallelism



New Trends in OS Design

- Active field of research
 - OS demand is growing (many computing devices are available)
 - New application settings (Web, Cloud, mobile, cars, etc.)
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- Open-source OS (Linux)
 - Allows developers to contribute to OS development
 - Excellent research platform to experiment with

Why Study OSs?

- To learn important concepts of computer science
 - **Abstraction**
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 - **How computers work**

Large Computer Systems

- The world is increasingly dependent on computer systems
 - Large, complex, interconnected, distributed, etc.

Large Computer Systems

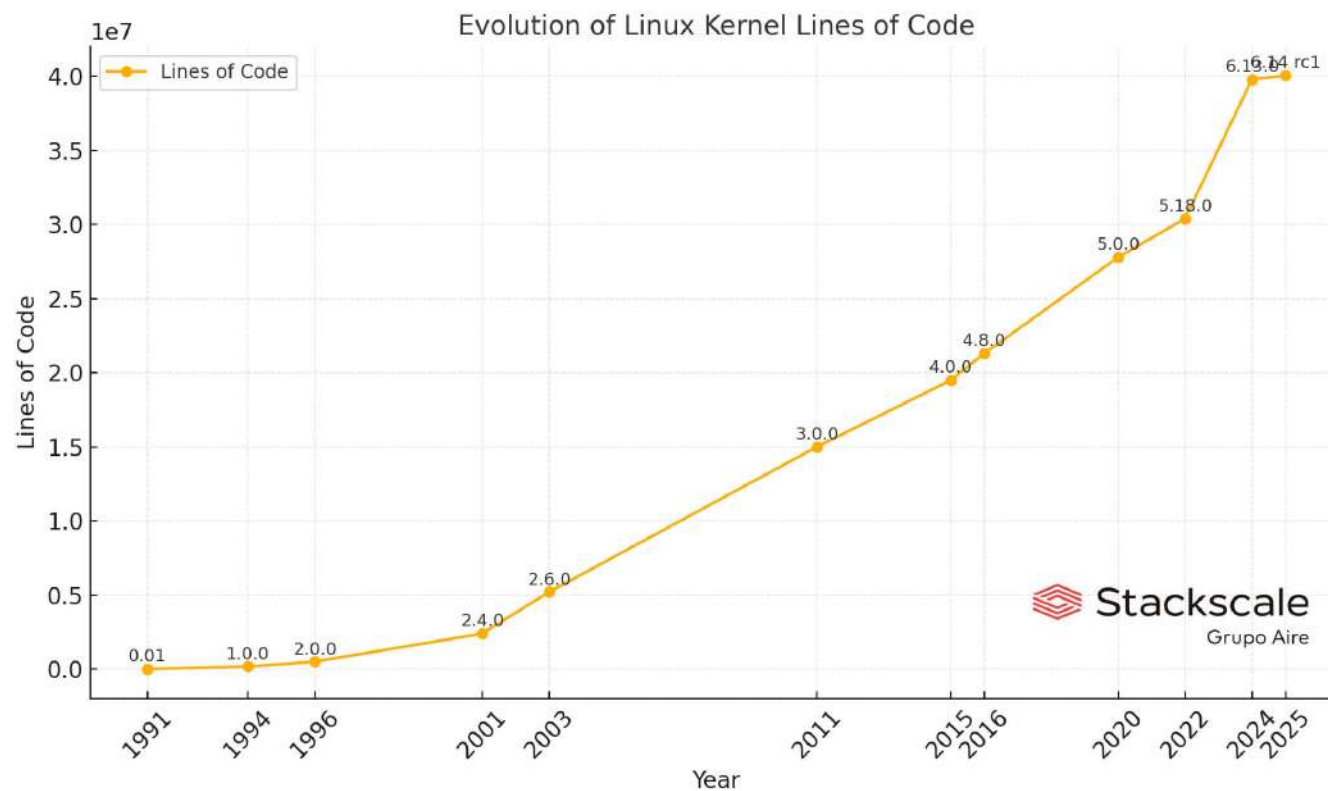
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OS is a great example of a large computer system

Linux Kernel Size (Lines of Code)



~40M LoC
as of 2025!

OS as Large Computer System

- Designing large computer systems requires you to know
 - **Each computer:**
 - Architectural details
 - High-level programming language (mostly, C/C++)
 - Memory management
 - Concurrency and scheduling
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 - **Across clusters of computers:**
 - Server architectures
 - Distributed file systems and computing frameworks

OS Design Issues (1)

- **Structure** → How the whole system is organized
- **Concurrency** → How parallel tasks are managed
- **Sharing** → How resources are shared
- **Naming** → How resources are identified by users
- **Protection** → How critical tasks are protected from each other
- **Security** → How to authenticate, authorize, and ensure privacy
- **Performance** → How to make it more efficient (quick, compact)

OS Design Issues (2)

- **Reliability** → How to deal with failures
- **Portability** → How to write once and run anywhere
- **Extensibility** → How to add new features/capabilities
- **Communication** → How to exchange information
- **Scalability** → How to scale up as demand increases
- **Persistency** → How to save task's status
- **Accounting** → How to claim on control resource usage

Architectural Trends: CPU

*Million Instructions Per Second

**1 MHz = 1,000,000 clock cycles per second

	1971 (Intel 4004)	Today (Intel Core i9)	Δ (orders of magnitude)
MIPS*	~0.09	~400,000+	+7
Instructions per clock cycle (1/CPI)	~0.12	~100+	+3
Clock frequency (MHz)**	0.74	~5,000	+4
Cheap size (μm)	10	0.014	-3

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Moore's law: the number of transistors in a dense integrated circuit doubles about every two years

Architectural Trends: Main Memory

	1973 (DEC PDP-8)	Today (Samsung DDR4)	Δ (orders of magnitude)
Capacity (kB)	12	128,000,000	+7
Cost (\$/MB)	~400,000	~0.005	-8

Architectural Trends: Disk

	1956 (IBM RAMAC 305)	Today (Western Digital)	Δ (orders of magnitude)
Capacity (MB)	5	15,000,000	+7
Size (inch)	24 (x50)	3.5	-3
Cost (\$/MB)	640 (per month)	~0.000018	-9

What's Next?

- Moore's law has hit its limit(?)
 - chip size has physical constraints
 - power vs. heat tradeoff
 - alternatives have already pushed forward the end of it:
 - multicore-manycore processors
 - other approaches are subject of research:
 - molecular/DNA transistors
 - quantum computing

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- A brief recap of how computer systems are organized
- Operating Systems as large and complex computer systems
- New architectural trends open up novel opportunities and challenges in Operating System design