

Systems and Networking – Unit I

B.Sc. in Applied Computer Science and Artificial Intelligence

2022-2023

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Sapienza Università di Roma

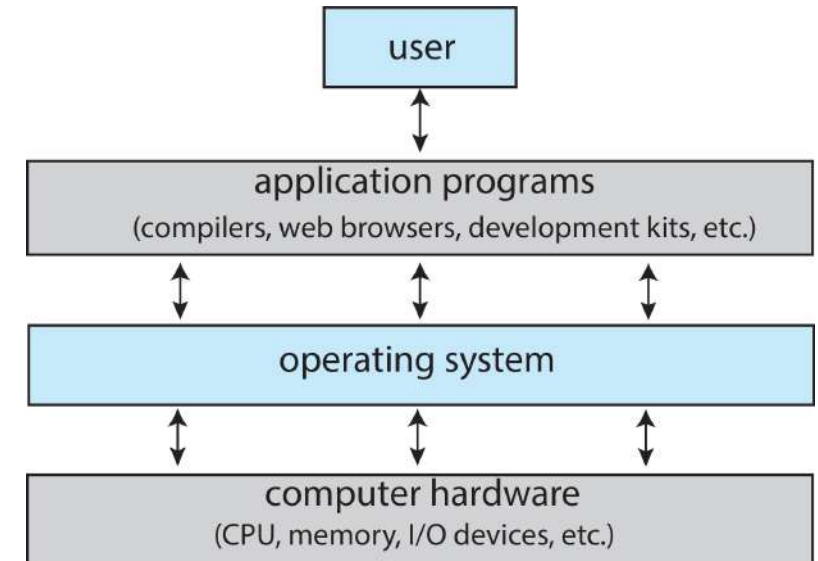
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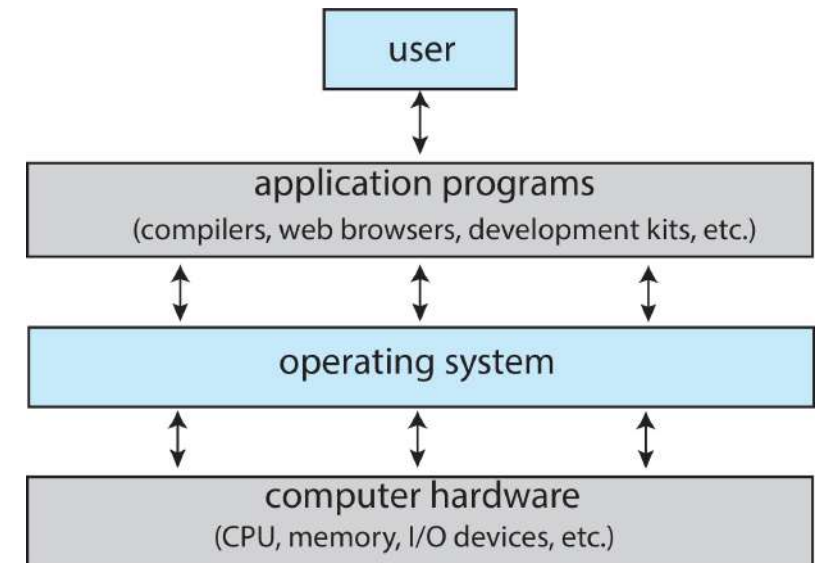
Recap from Last Lecture

- Operating System is a complex system which plays several roles:
 - resource manager
 - virtual machine
 - HW/SW interface



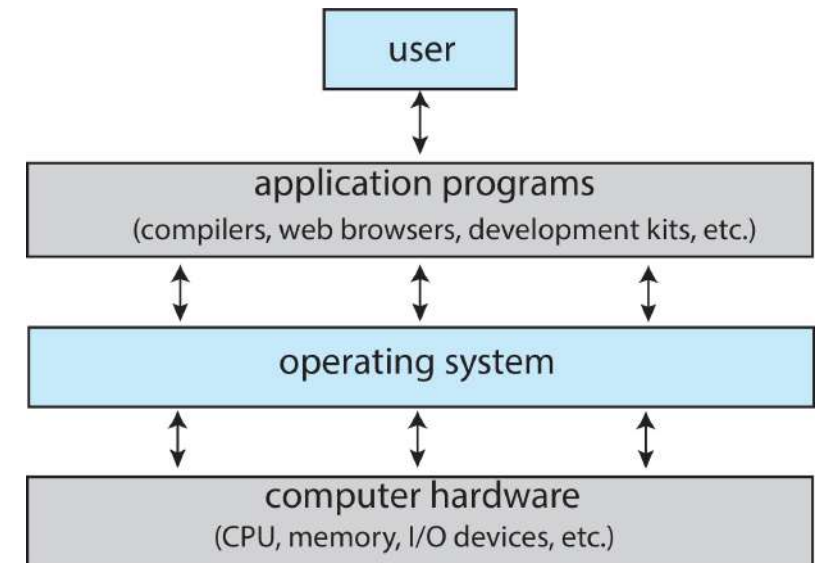
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- Changes in HW may affect OS design



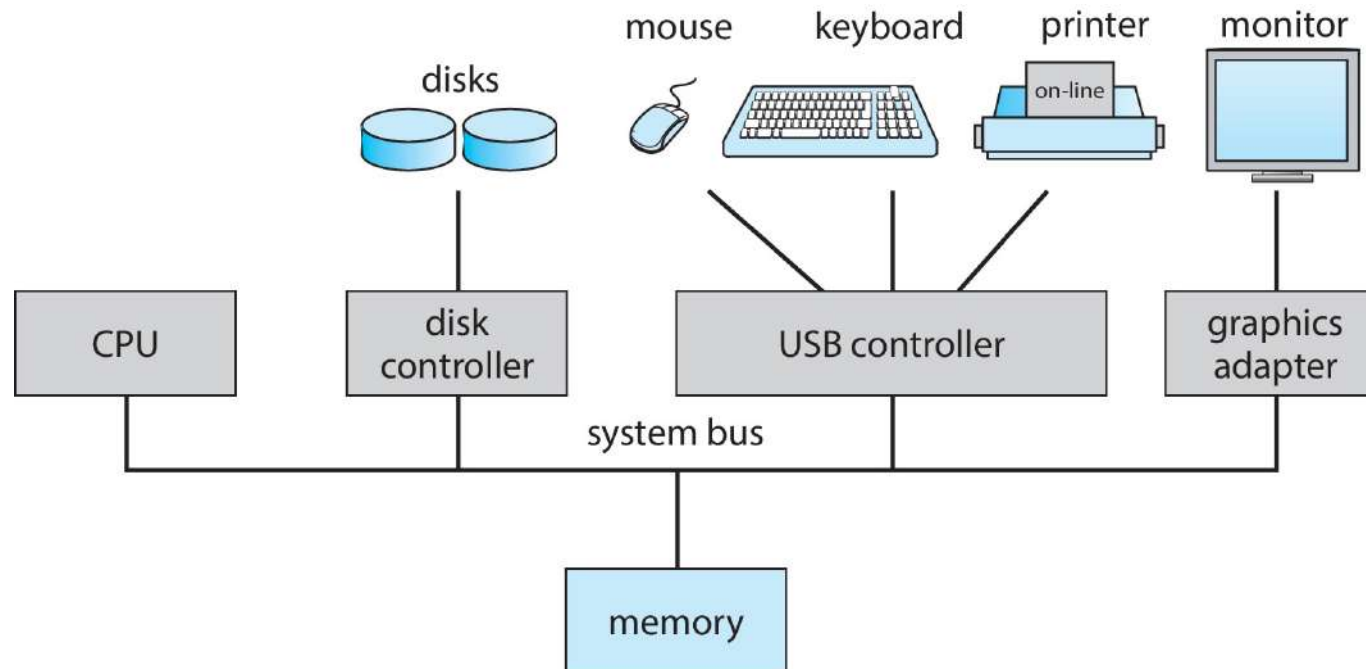
Outline of this Lecture

1. Computer architecture review
2. HW support for OS functionalities and services
3. OS design and implementation

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Generic High-Level Computer Architecture



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- **I/O devices** → terminal, keyboard, disks, etc.
 - associated with specific device controllers
- **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
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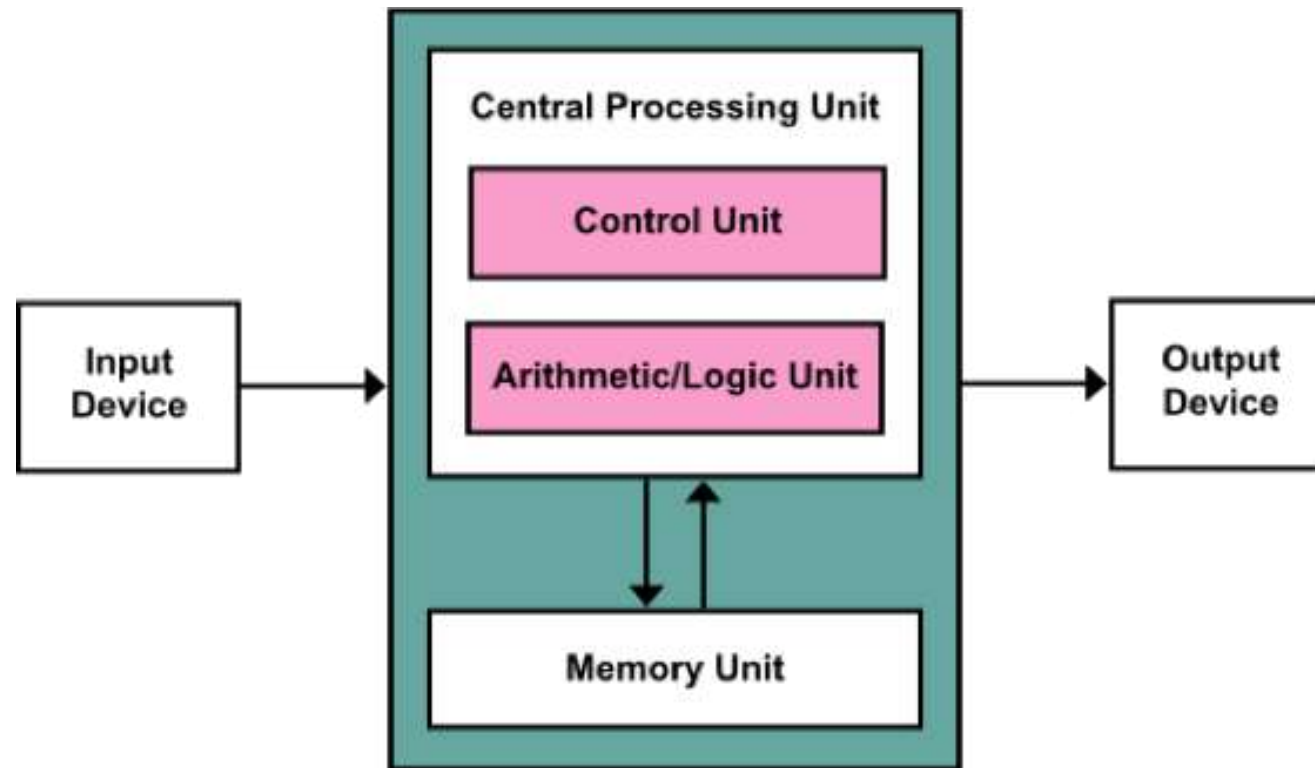
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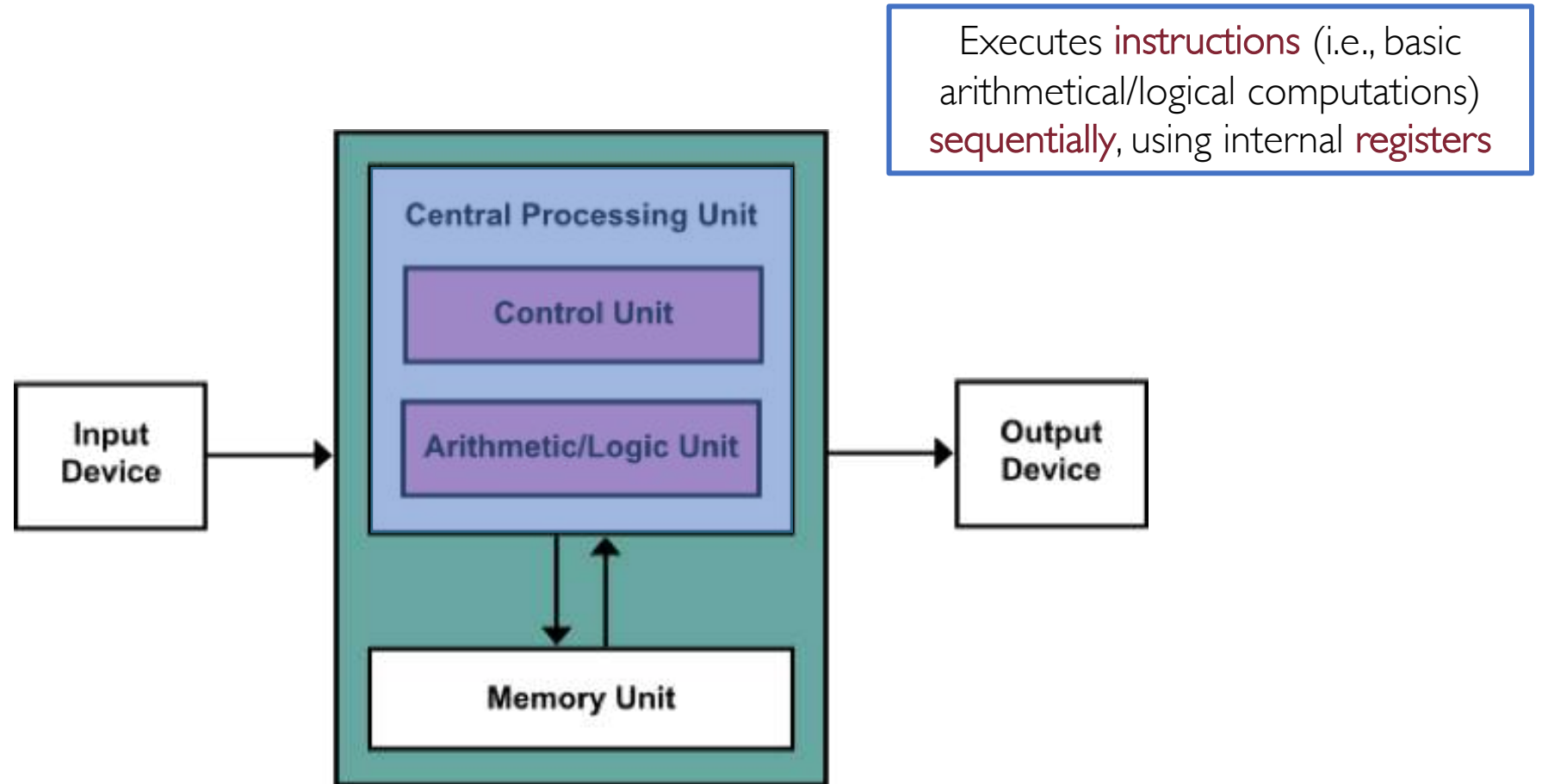


John von Neumann

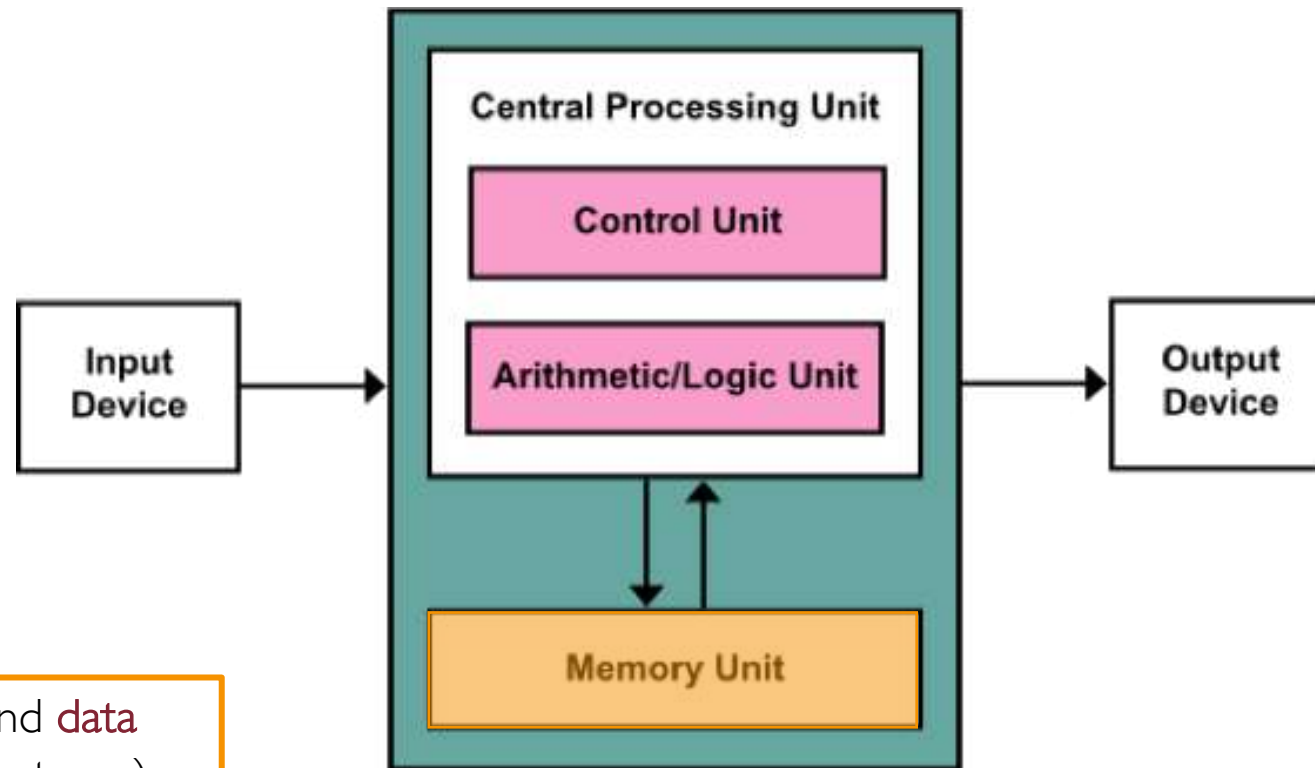
von Neumann Architecture



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

Central Processing Unit (CPU)

Instruction Cycle: Fetch-Decode-Execute

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 - **Execute:** runs the actual decoded instruction

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

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$$1 \cdot 10^0 + 0 \cdot 10^1 + 1 \cdot 10^2 = 101$$

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- In binary system (base-2), each digit is a bit

1	0	1
---	---	---

$$1 \cdot 2^0 + 0 \cdot 2^1 + 1 \cdot 2^2 = 5$$

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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- Each realization of the same instruction set is an implementation of a physical architecture (e.g., x86 → Intel, AMD, Cyrix, etc.)

CPU Registers

- On-chip storage whose size typically coincides with the CPU word size

CPU Registers

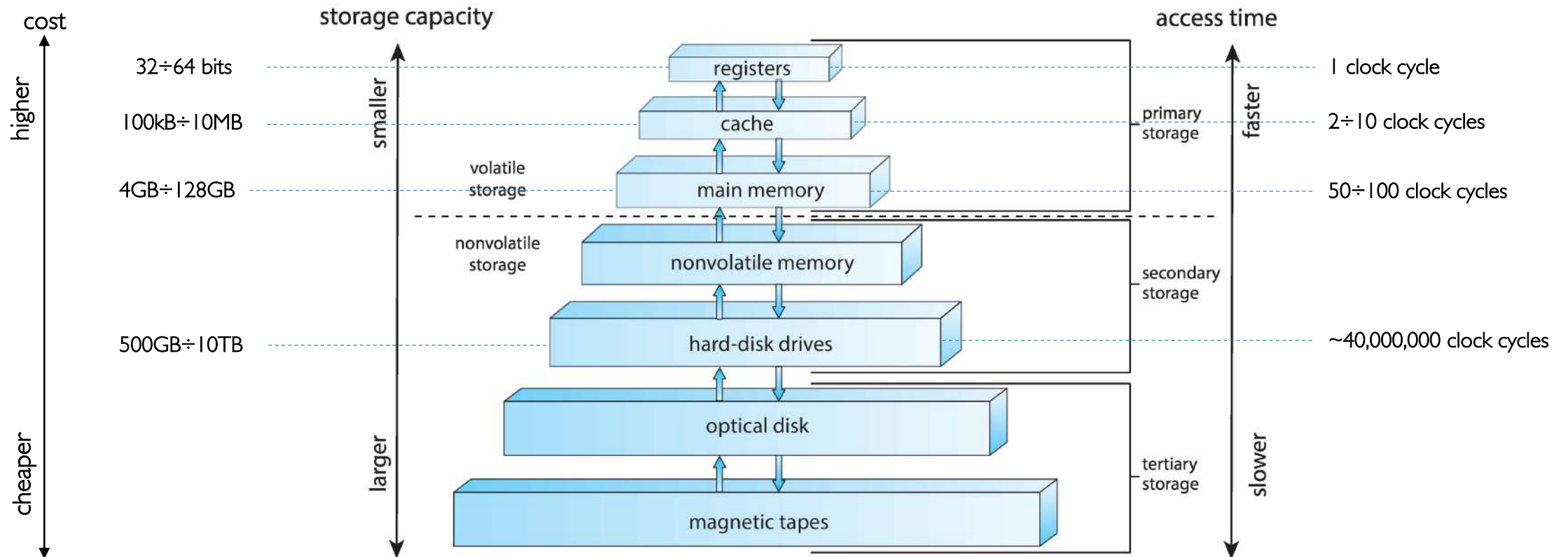
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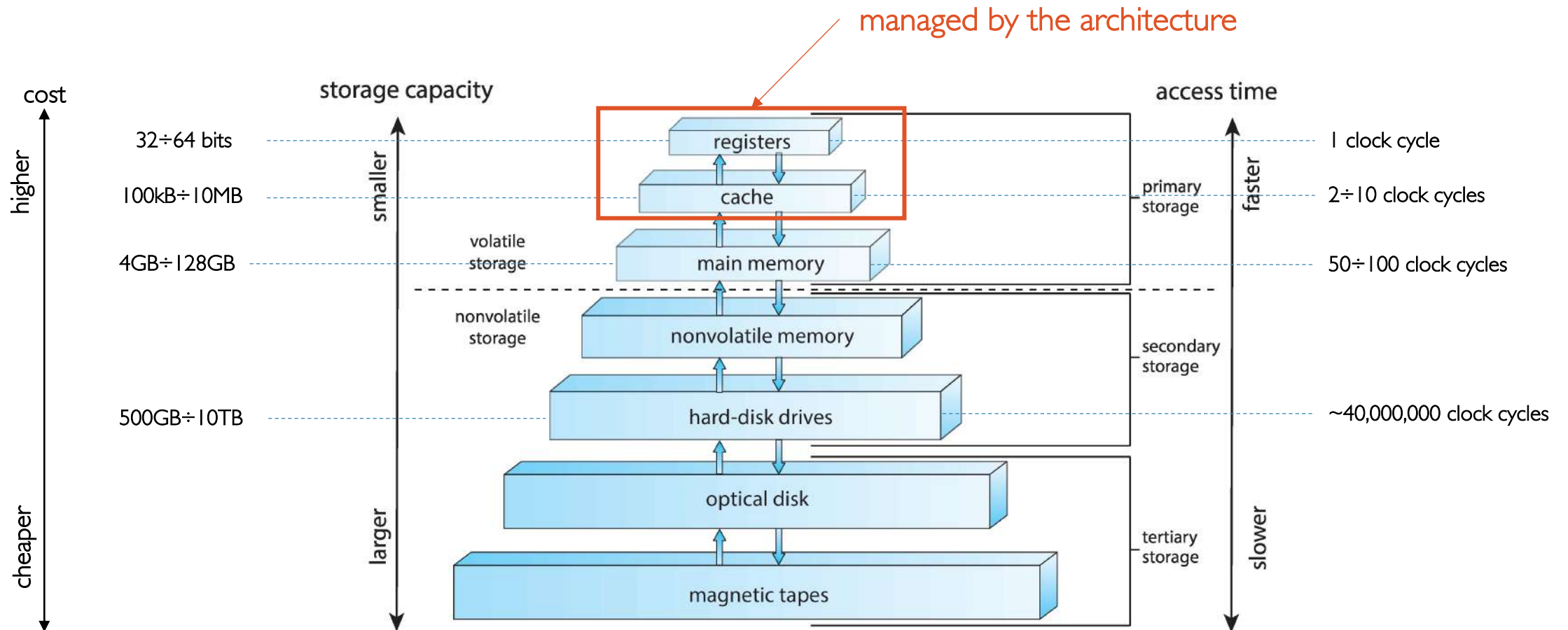
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- Special-purpose (x86):
 - `esp` → Stack pointer for top address of the stack
 - `ebp` → Stack base pointer for the address of the current stack frame
 - `eip` → Instruction pointer, holds the program counter (i.e., the address of next instruction)

Memory

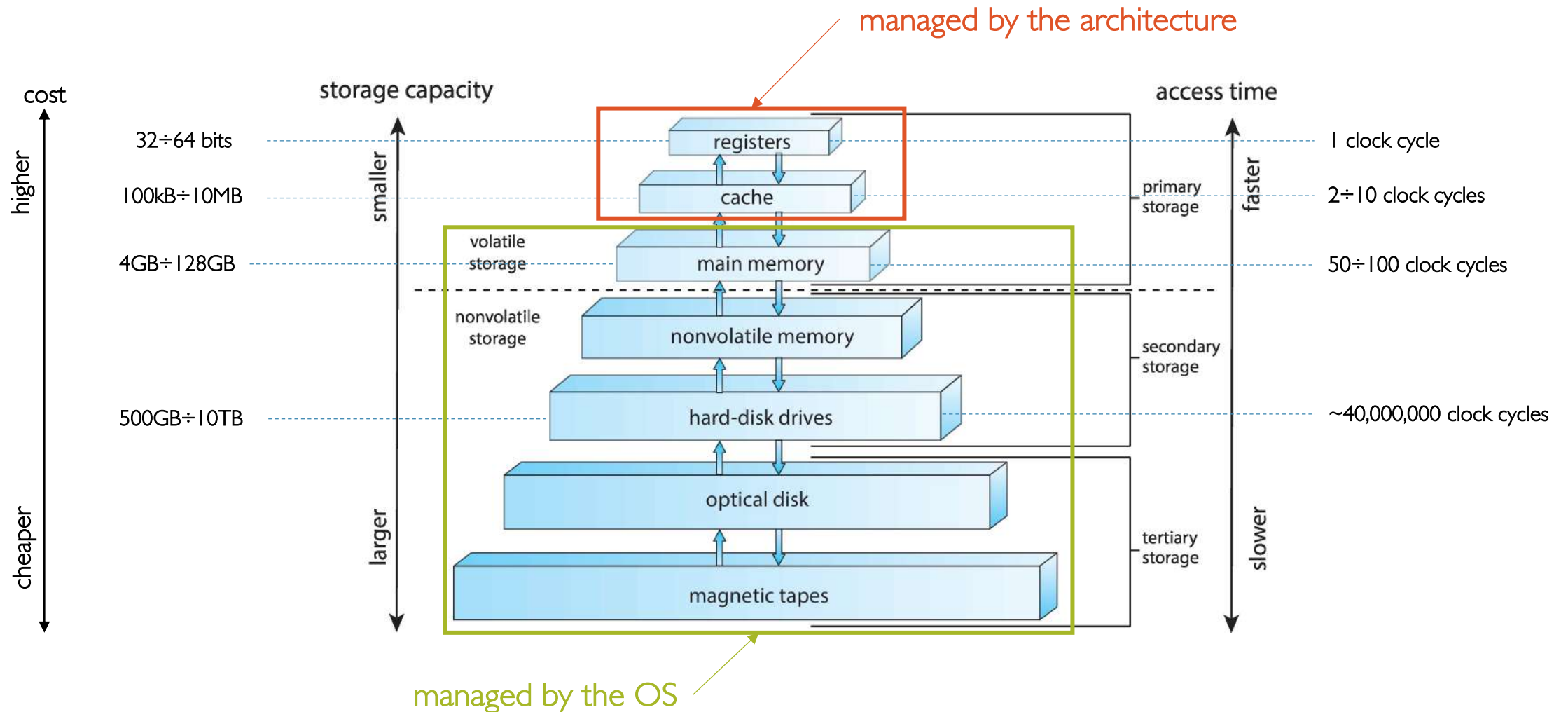
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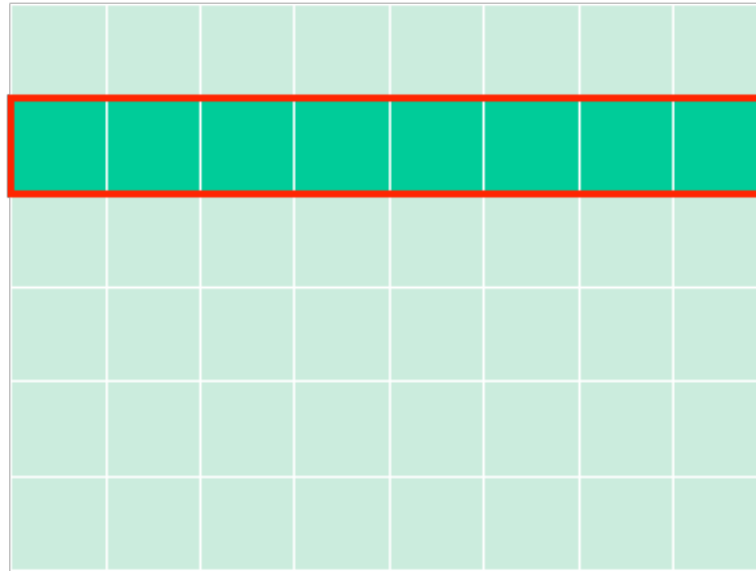
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- The smallest addressable unit is usually 1 Byte

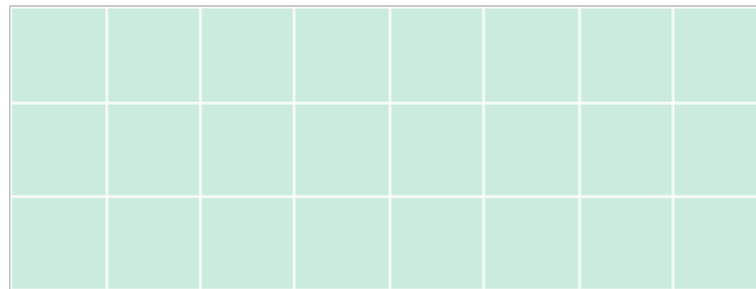
Memory Cell (I)

Cell/Location



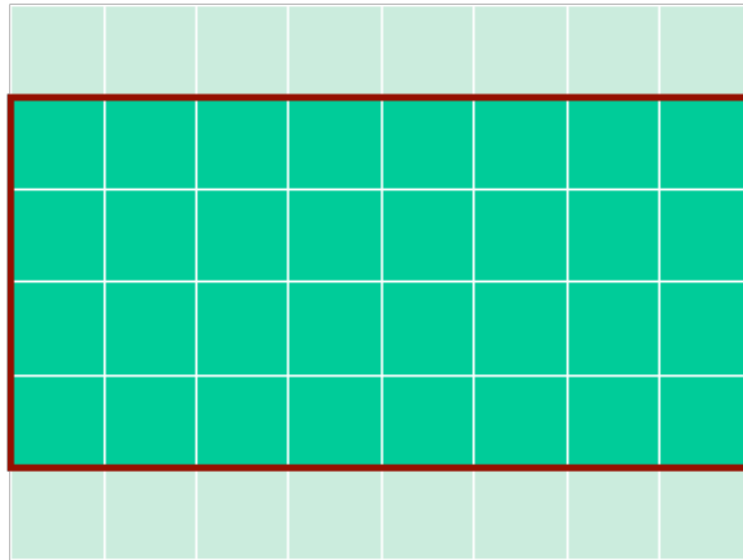
8 bits = 1 Byte

...



Memory Cell (2)

Cell/Location



32 bits = 4 Bytes

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

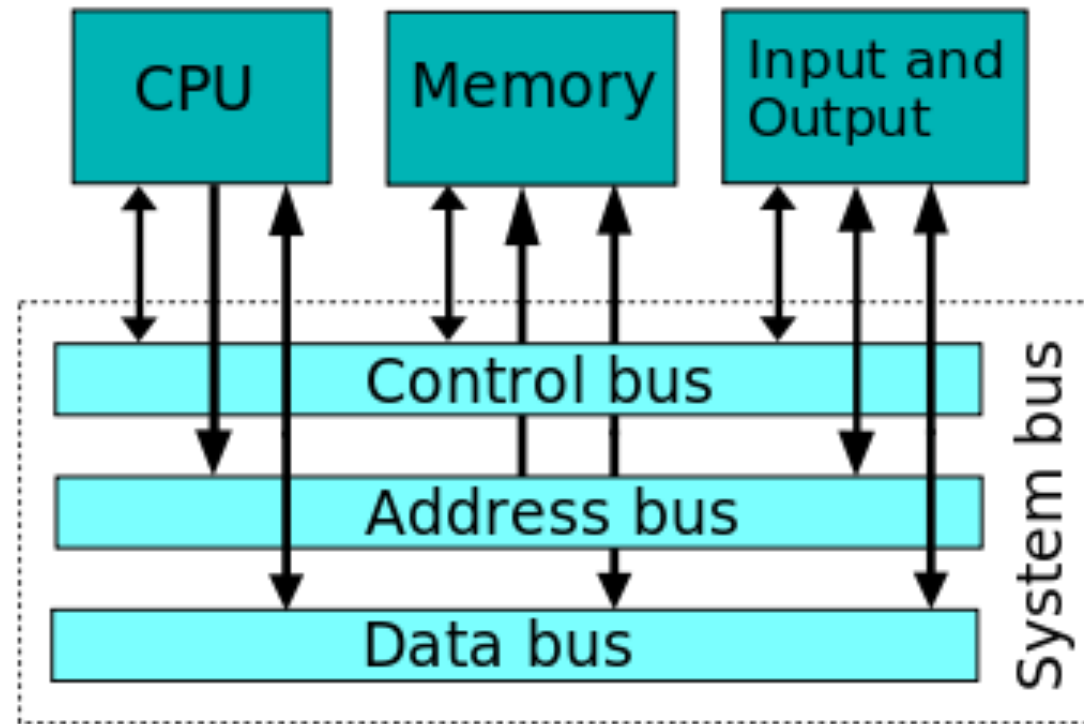
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- More dedicated buses have been added to manage CPU-to-memory and I/O traffic
 - PCI, SATA, USB, etc.

System Bus



I/O Devices

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

Device Drivers: OS Software Abstraction

hardware



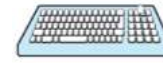
SATA disks



IDE disks



mouse



keyboard

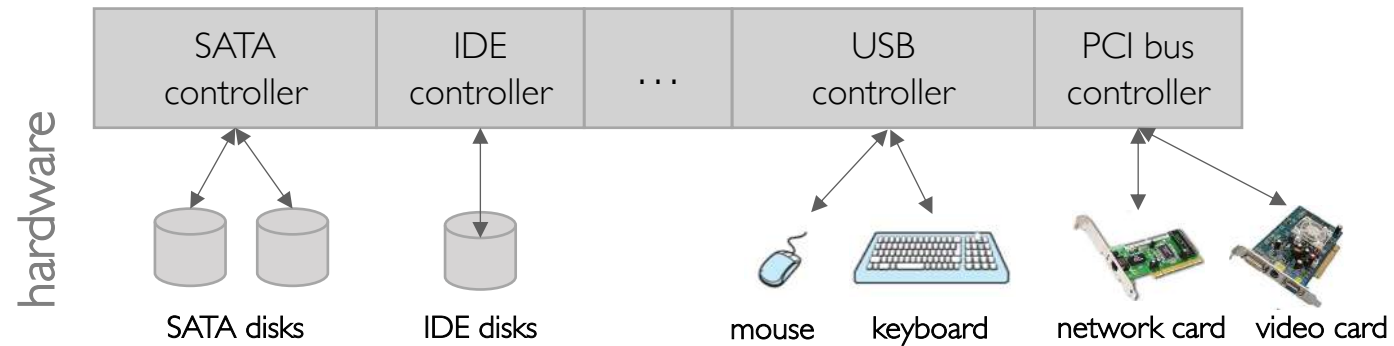


network card

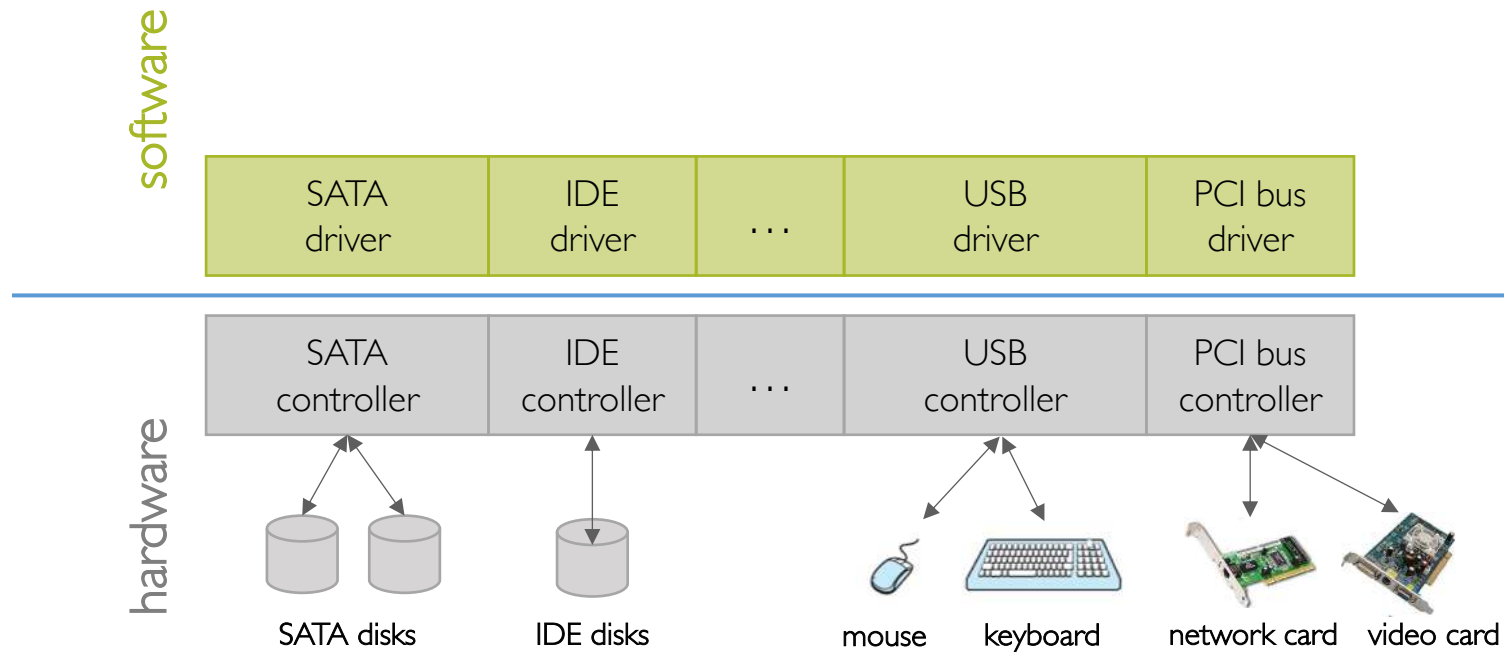


video card

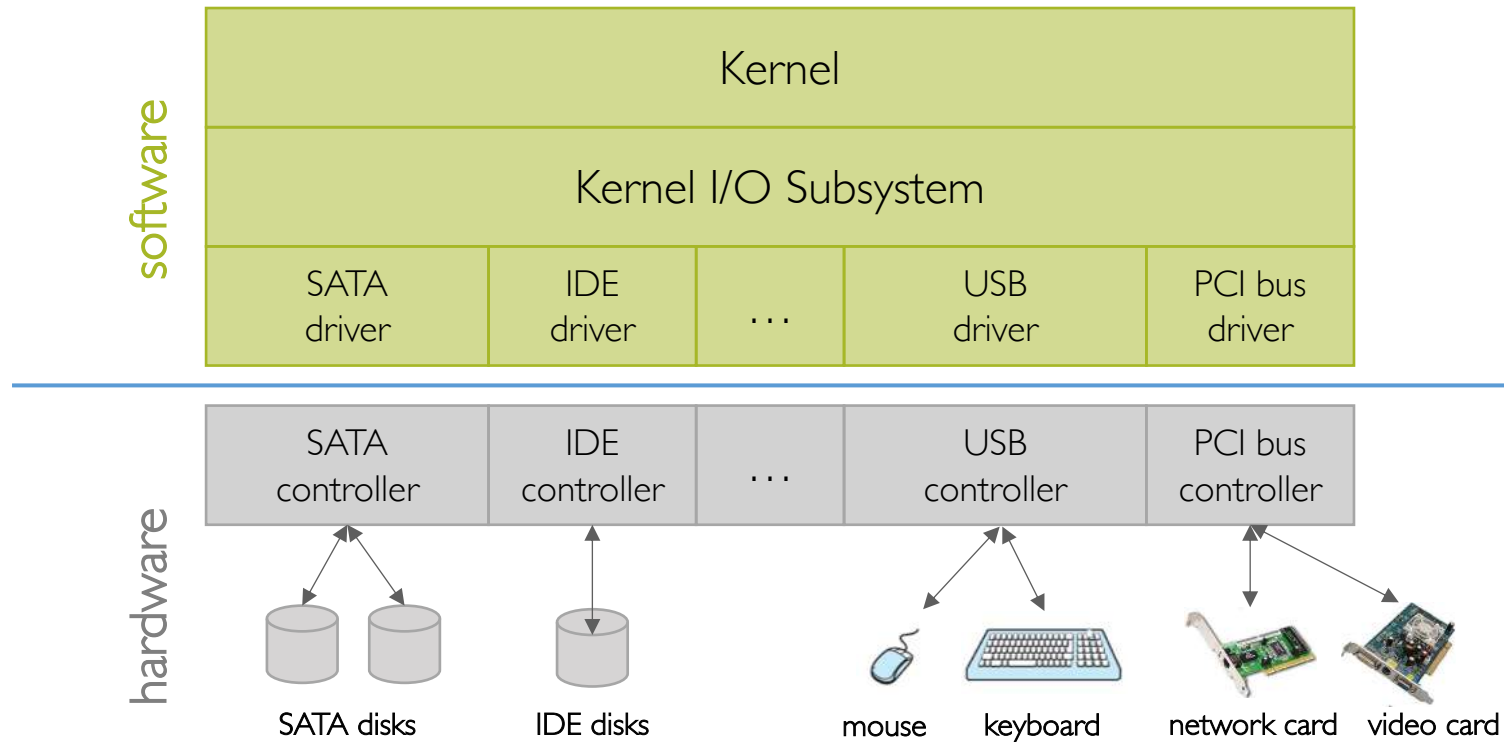
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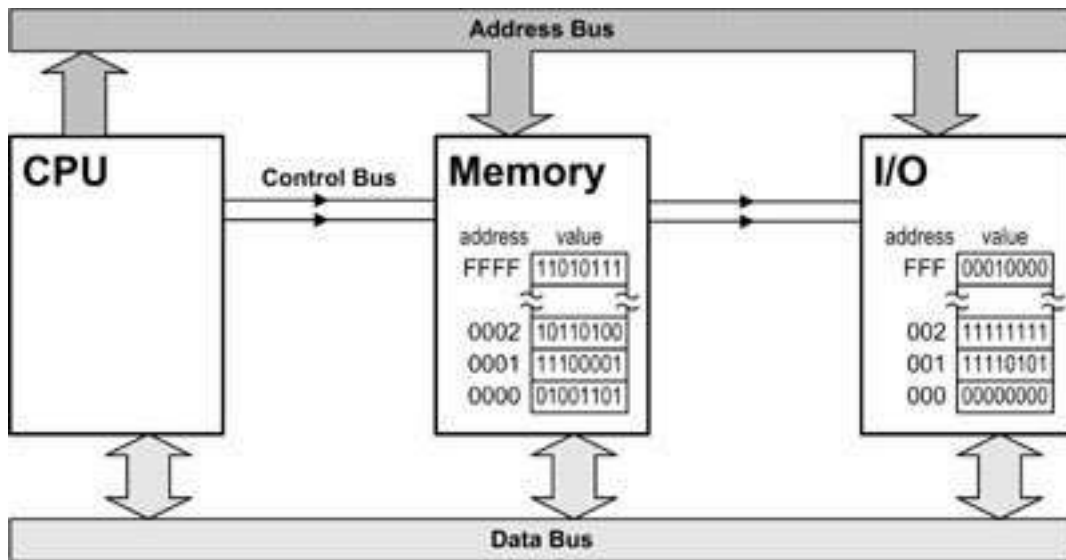
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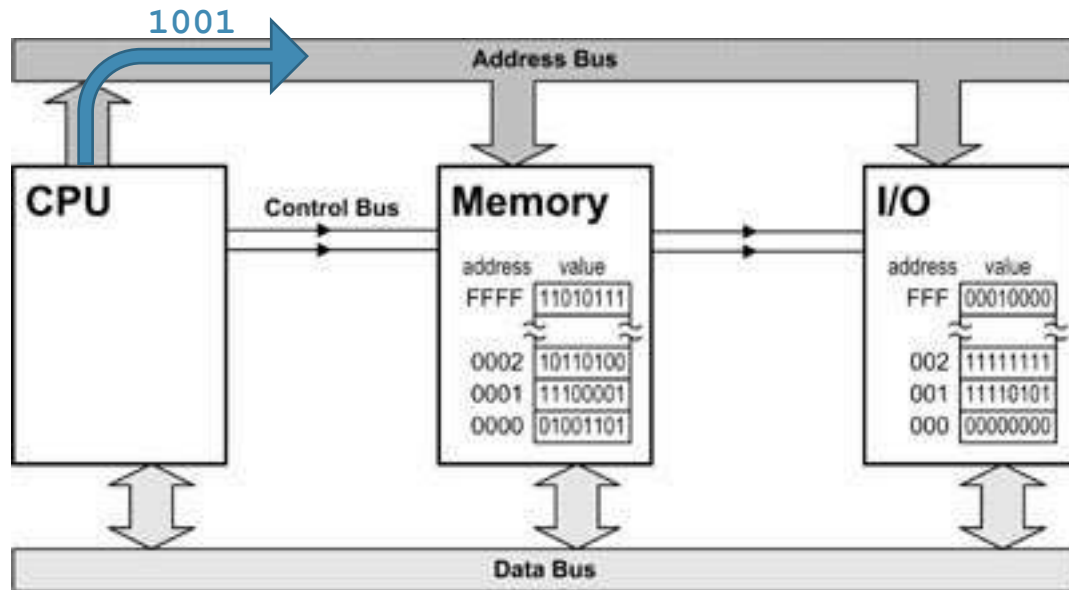
How does the CPU know how to address (registers of) I/O devices?

Addressing Using the System Bus

How does CPU reference Memory addresses?



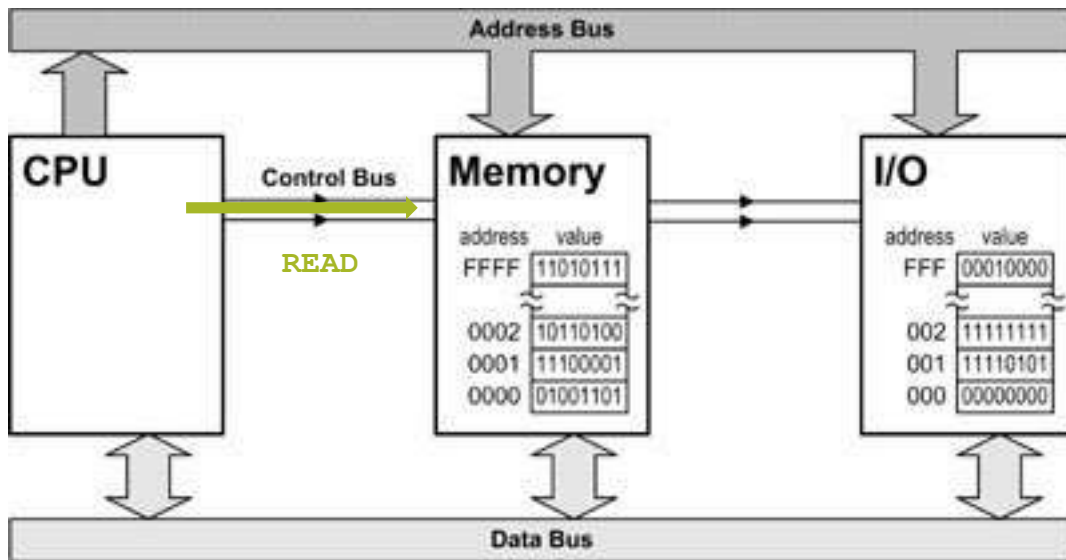
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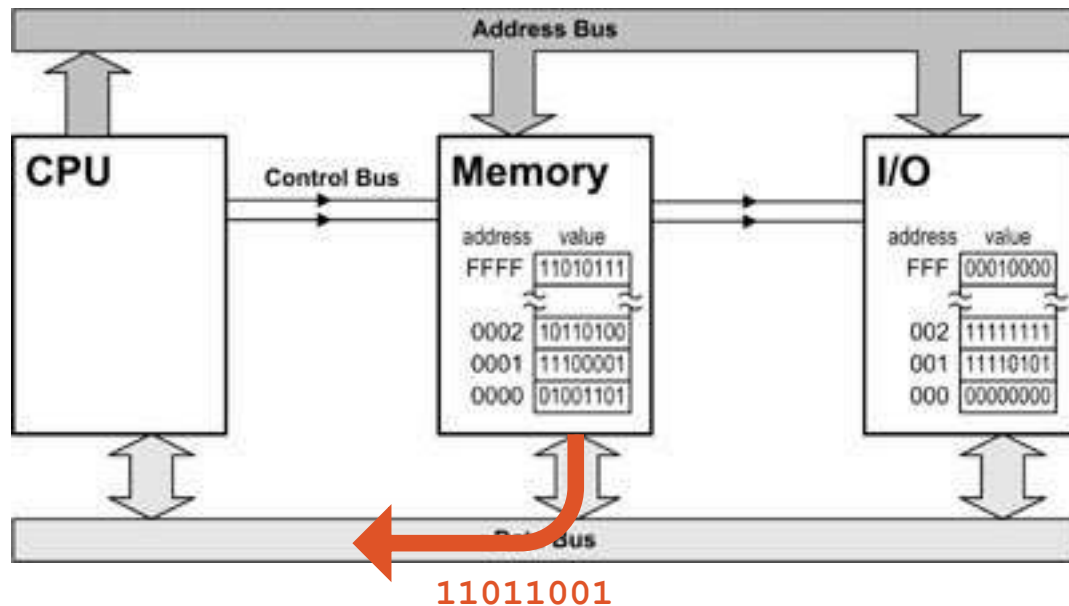


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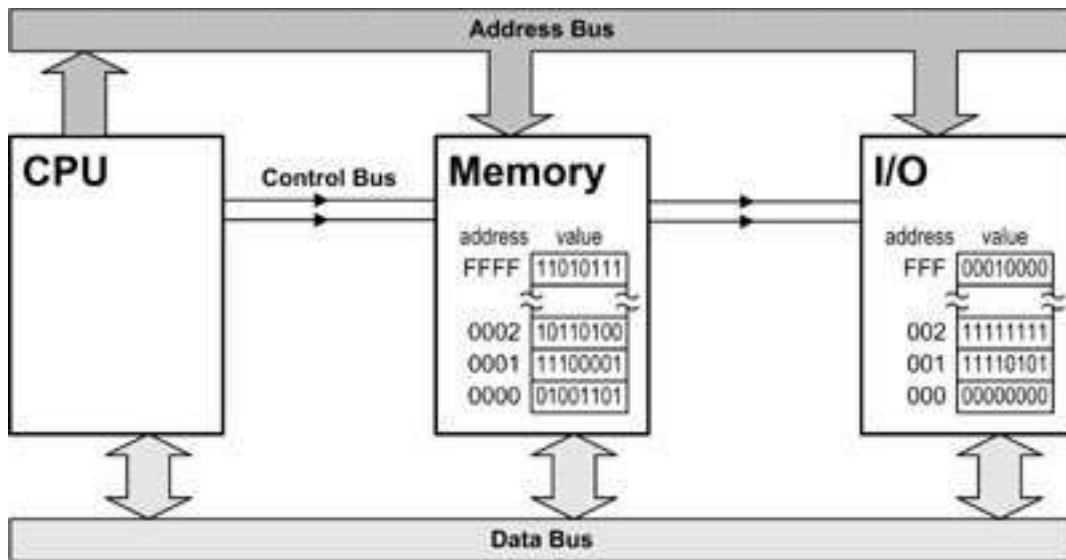
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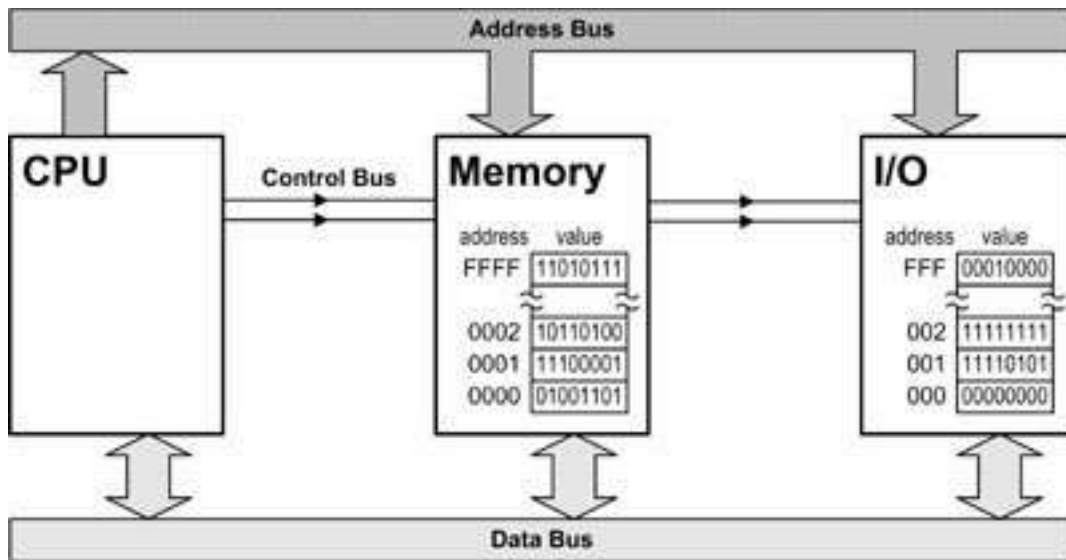
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The control bus has a special line called "**M/#IO**" which asserts whether the CPU wants to talk to memory or an I/O device

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 - **Port-mapped I/O** → referencing controller's registers using a separate I/O address space
 - **Memory-mapped I/O** → mapping controller's registers to the same address space used for main memory

Port-Mapped I/O

- Each I/O device controller's register is mapped to a specific port (address)
- Requires special class of CPU instructions (e.g., **IN**/**OUT**)
 - The **IN** instruction reads from an I/O device, **OUT** writes
- When you use the **IN** or **OUT** instructions, the **M/#IO** is not asserted, so memory does not respond and the I/O chip does

Memory-Mapped I/O

- Memory-mapped I/O "wastes" some address space but doesn't need any special instruction
- To the CPU I/O device ports are just like normal memory addresses
- The CPU use MOV-like instructions to access I/O device registers
- In this way, the **M/#IO** is asserted indicating the address requested by the CPU refers to main memory

Port- vs. Memory-Mapped I/O

```
MOV DX,1234h  
MOV AL,[DX]    ;reads memory address 1234h (memory address space)  
IN AL,DX       ;reads I/O port 1234h (I/O address space)
```

Both put the value **1234h** on the CPU address bus, and both assert a **READ** operation on control bus

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The first one will assert **M/#IO** to indicate that the address belongs to memory address space

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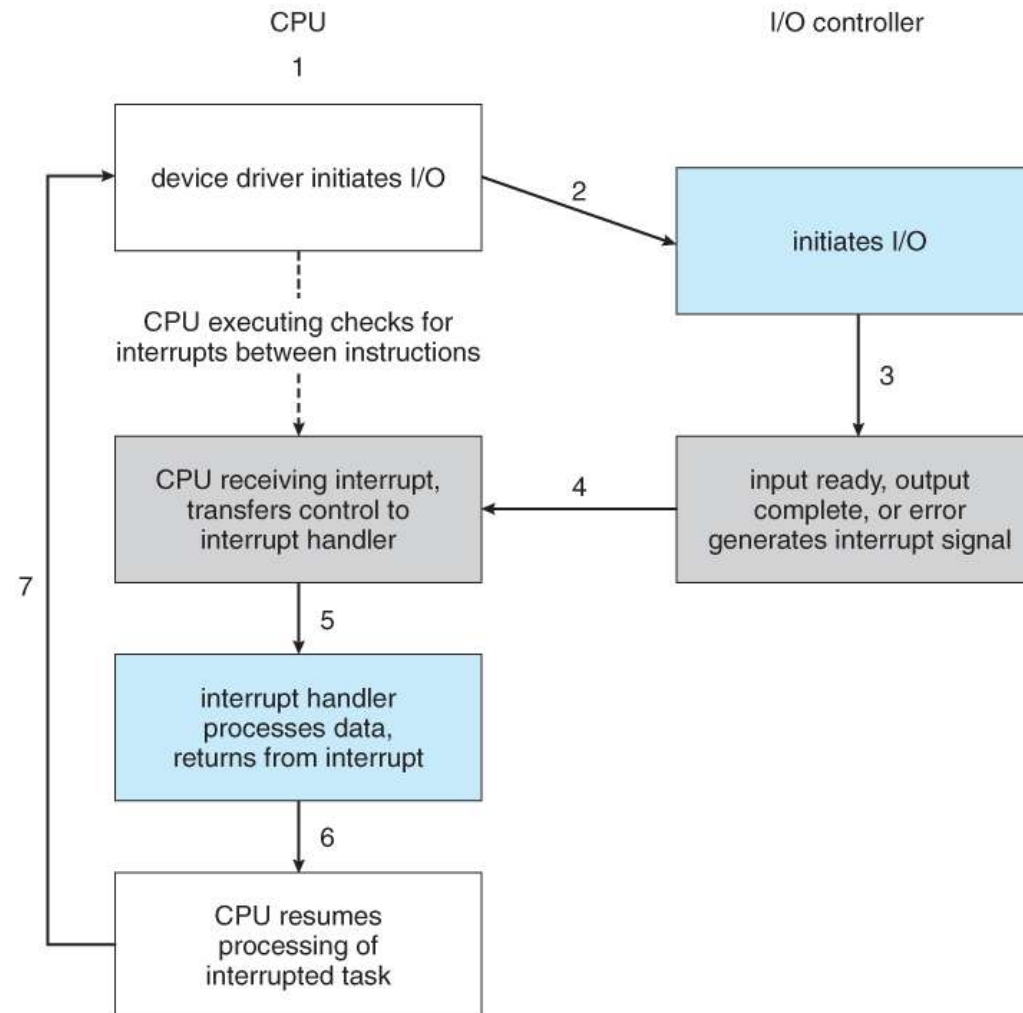
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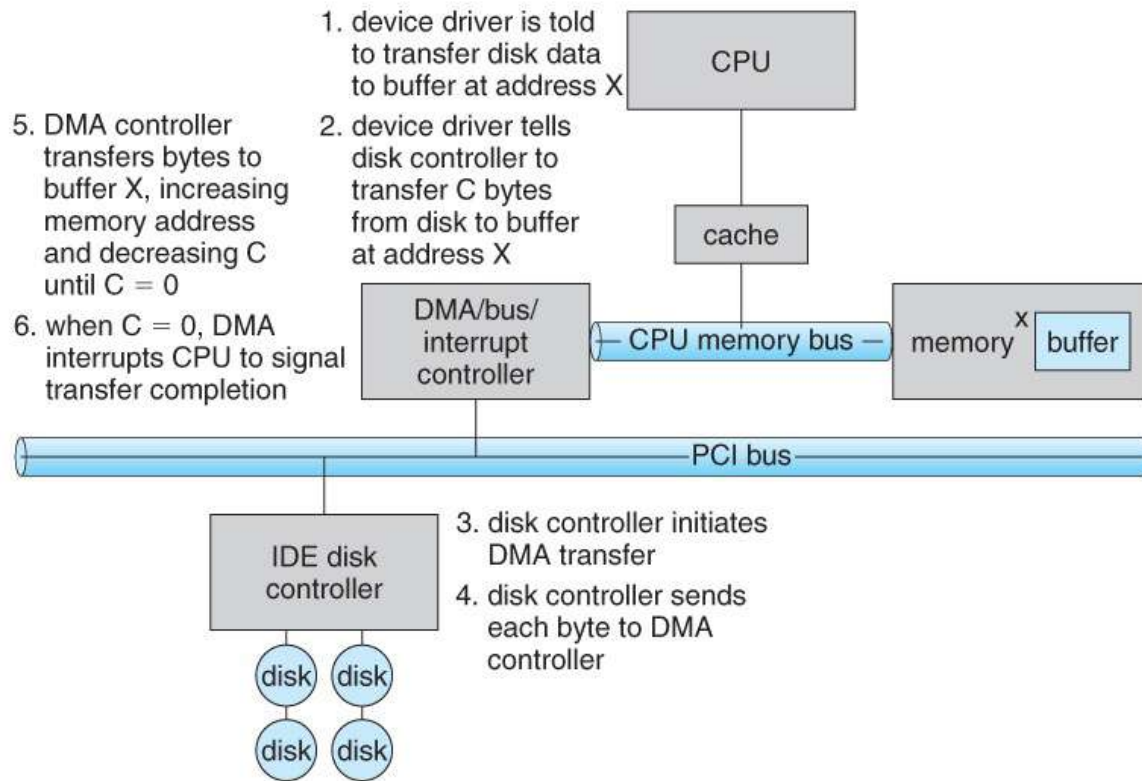
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WHO?

How: Interrupt-driven I/O



Who: Direct Memory Access (DMA)



Overcome the limitation of Programmed I/O

Maybe wasteful to tie up the CPU transferring data in and out of registers **one byte at a time**

Useful for devices that transfer large quantities of data (such as disk controllers)

Typically, used in combination with **interrupt-driven I/O**

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3. OS design and implementation

OS and Computer Architecture

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- Architectural support may significantly simplify or complicate the OS design

Architectural Features Enabling OS Services

OS Service	HW Support
Protection and Security	Kernel/user mode, protected instructions, base/limit registers
System calls	Trap instructions and interrupt vectors
Exception handling	Trap instructions and interrupt vectors
I/O operations	Trap instructions, interrupt vectors, and memory mapping
Scheduling	Timer
Synchronization	Atomic instructions
Virtual memory	Translation Look-aside Buffer (TLB)

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Privileged Instructions

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 - `MOV %eax, %ebx` → move the content of the register `ebx` into `eax`
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Idea: sensitive (privileged) instructions can be executed only by the OS

Kernel vs. User Mode

- 2 different "states" while executing CPU instructions

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Implemented in HW!
A status bit stored in a protected CPU register
(0=kernel, 1=user)

Beyond Kernel vs. User Mode

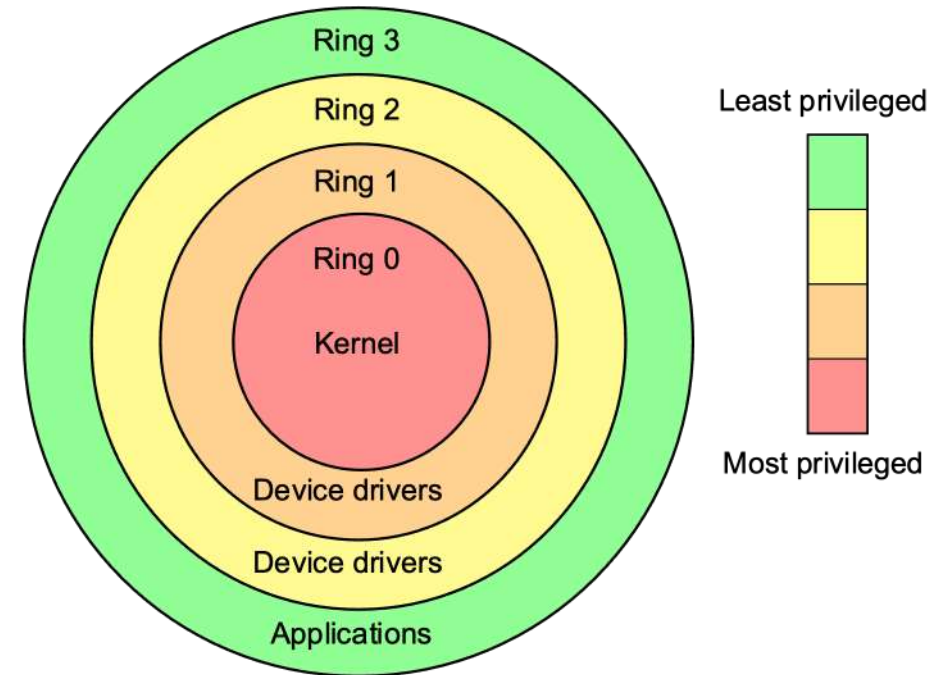
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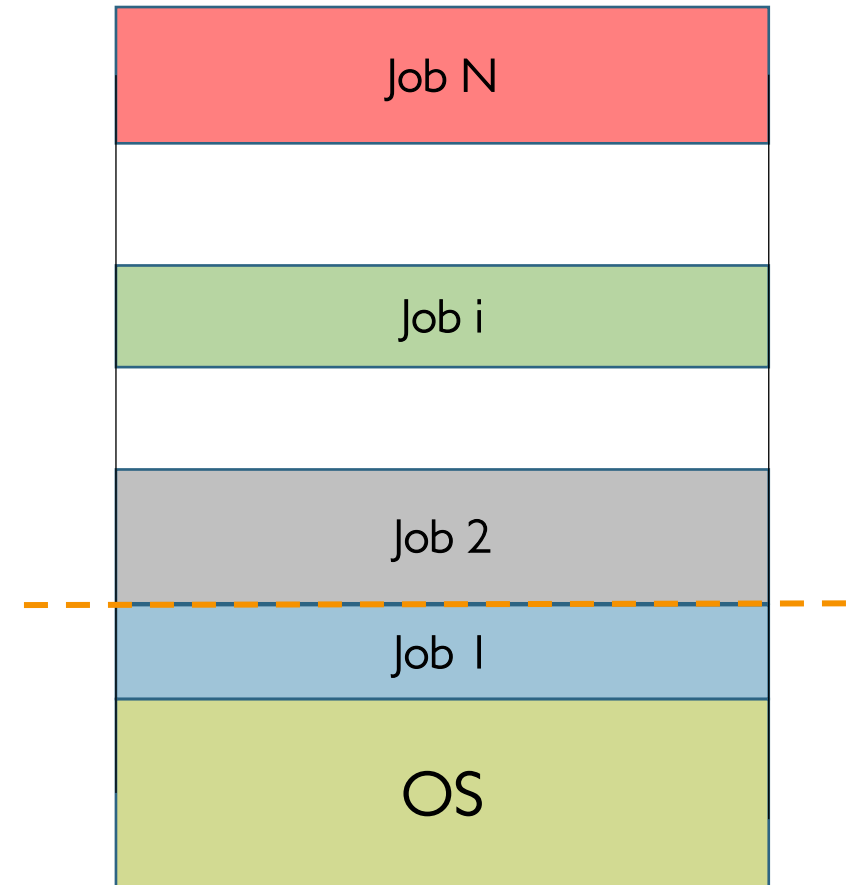
Beyond Kernel vs. User Mode

- The underlying HW must support at least kernel and user mode
- More fine-grained solutions are also possible
- **Protection Rings**
 - 4 different privilege levels $\{0, \dots, 3\}$
 - Still implementable in HW (2 bits)



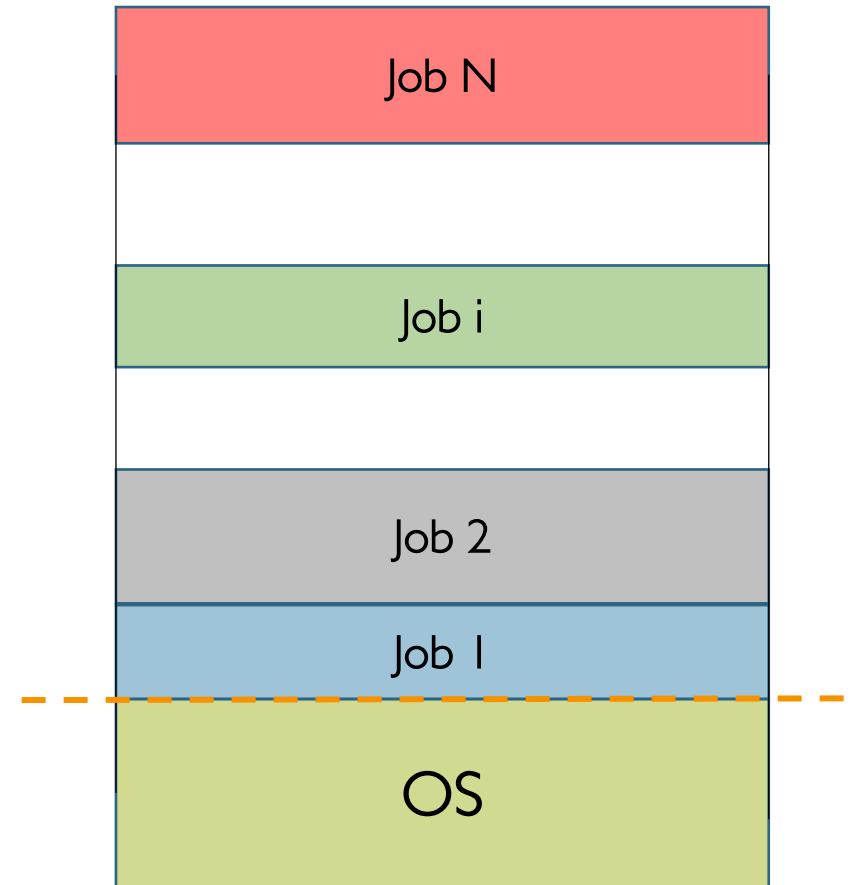
Memory Protection

- Architecture must provide support for the OS to:
 - Protect user programs from each other



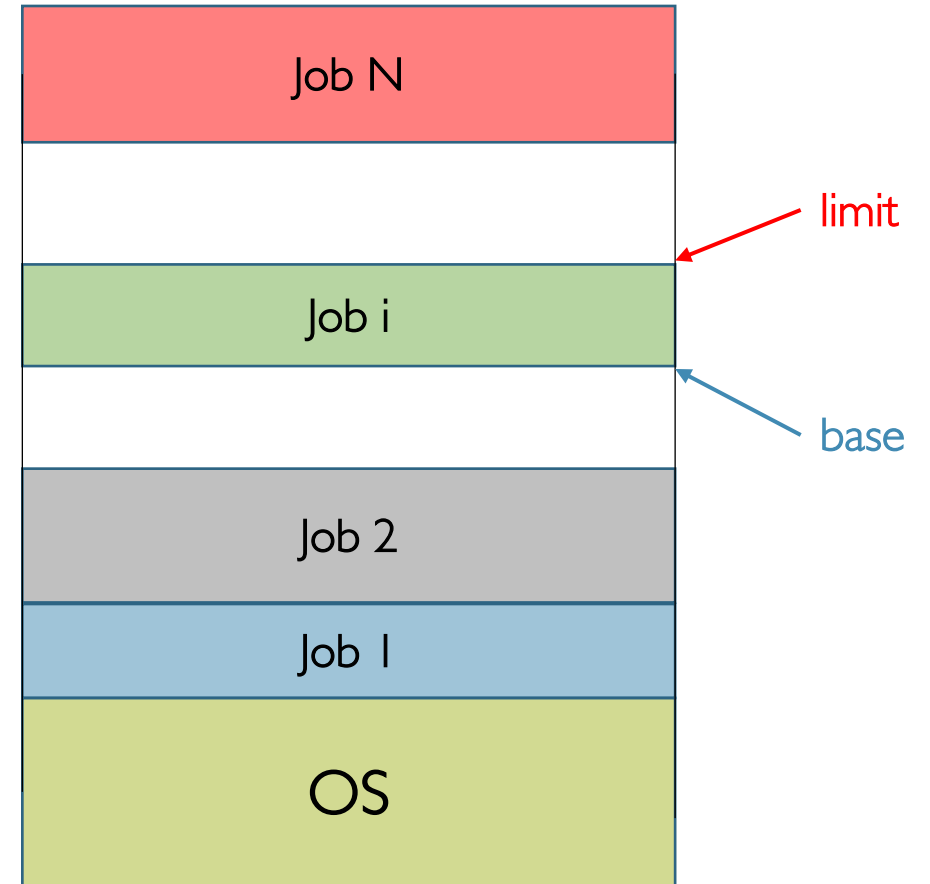
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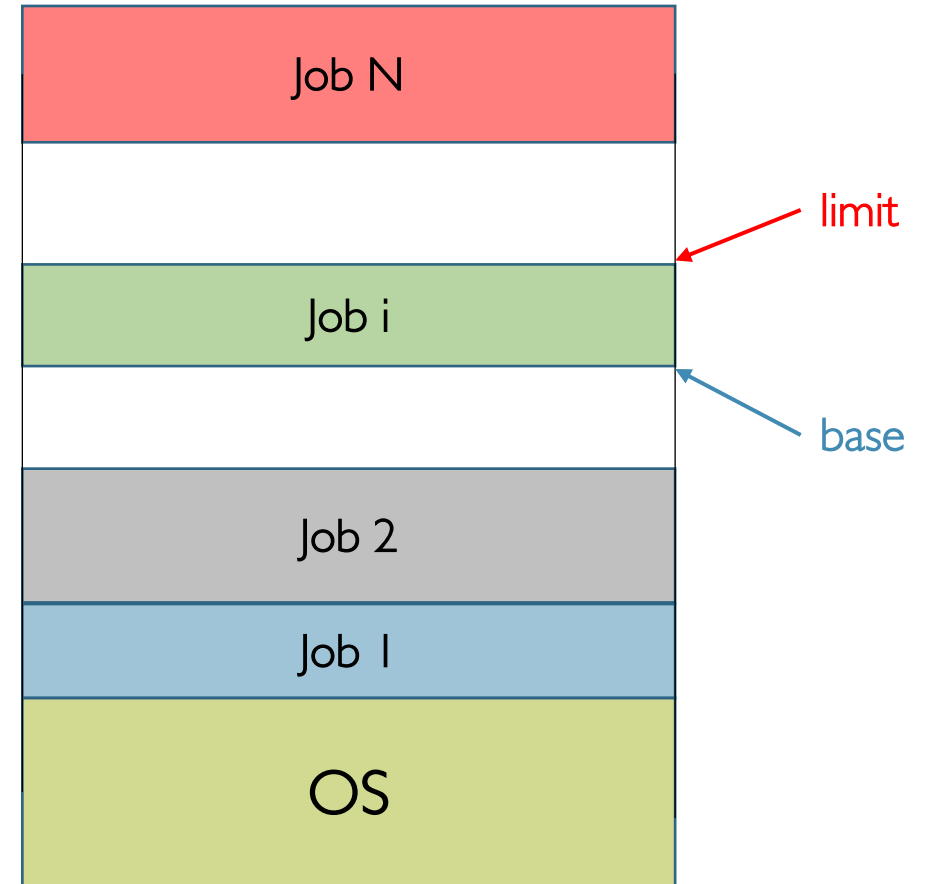
Memory Protection

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 - **base** → contains the starting valid memory address
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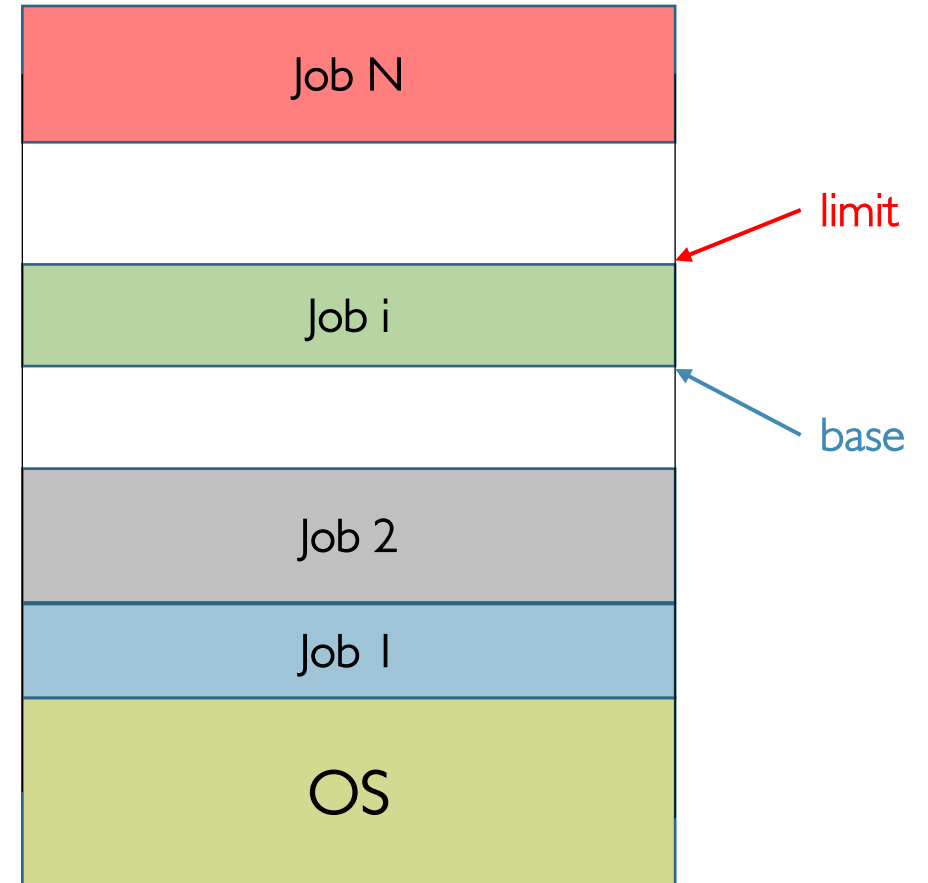
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- The OS loads the **base** and **limit** registers upon program startup
- The CPU checks each memory address referenced by user program falls between **base** and **limit** values



Architectural Features Enabling OS Services

OS Service	HW Support
Protection and Security	Kernel/user mode, protected instructions, base/limit registers
System calls	Trap instructions and interrupt vectors
Exception handling	Trap instructions and interrupt vectors
I/O operations	Trap instructions, interrupt vectors, and memory mapping
Scheduling	Timer
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Crossing protection boundaries using **system calls**

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- Interrupts

- hardware-generated (by external devices)
- e.g., I/O completion or timer interrupt on a multi-tasking system

A Quick Note on Terminology



TRAP

We will refer to **trap** as any event that causes switch to OS kernel mode

A Quick Note on Terminology

TRAP

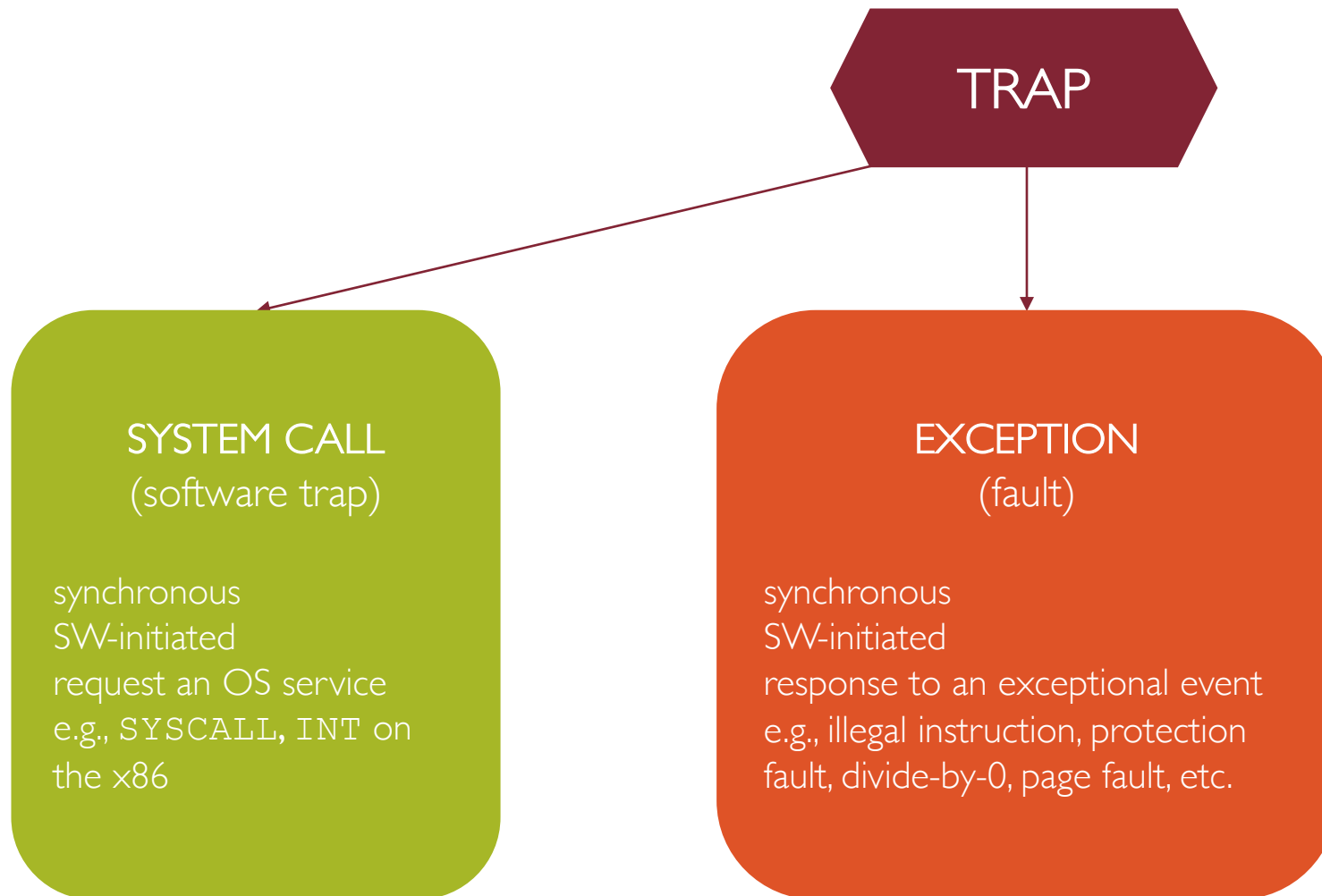


```
graph TD; TRAP[TRAP] --> SC[SYSTEM CALL<br/>(software trap)<br/>synchronous<br/>SW-initiated<br/>request an OS service<br/>e.g., SYSCALL, INT on<br/>the x86];
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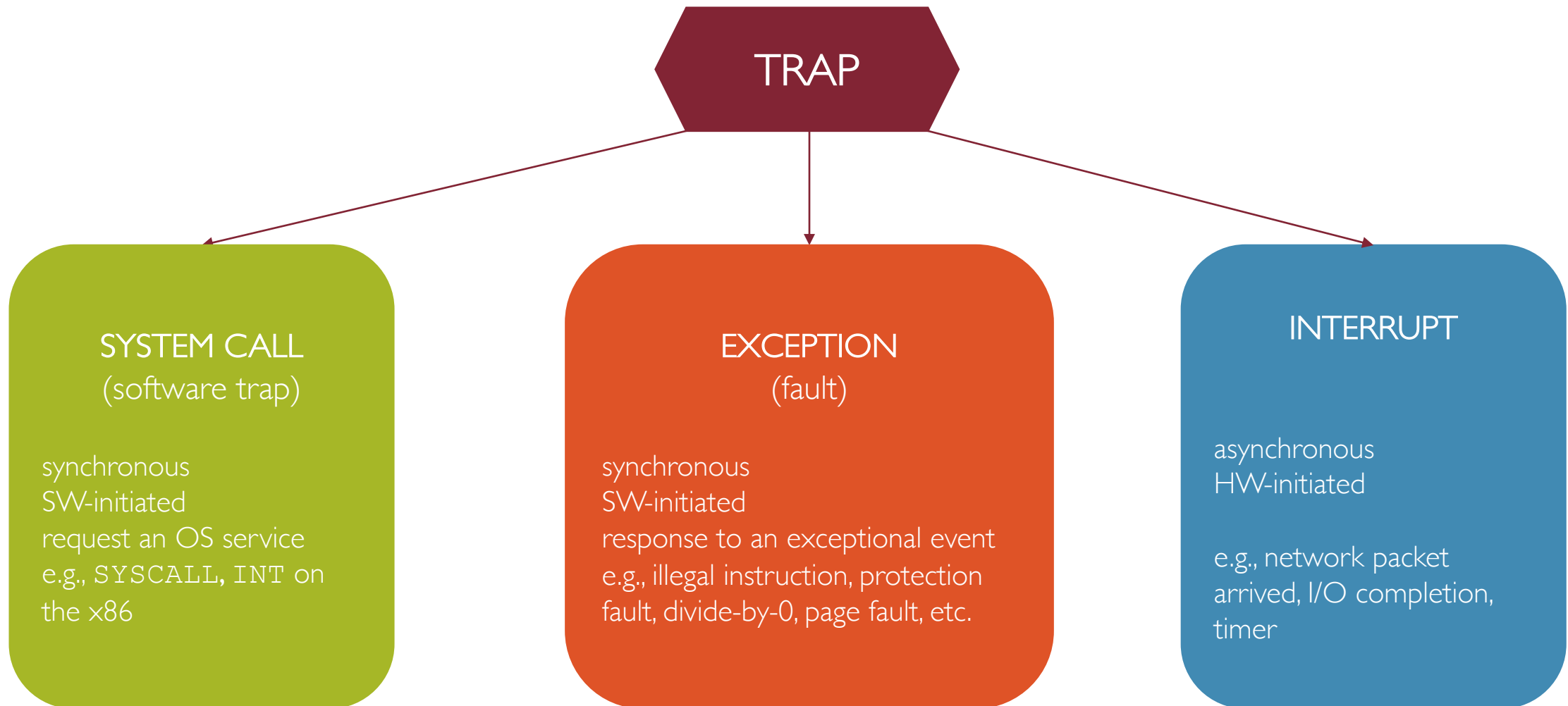
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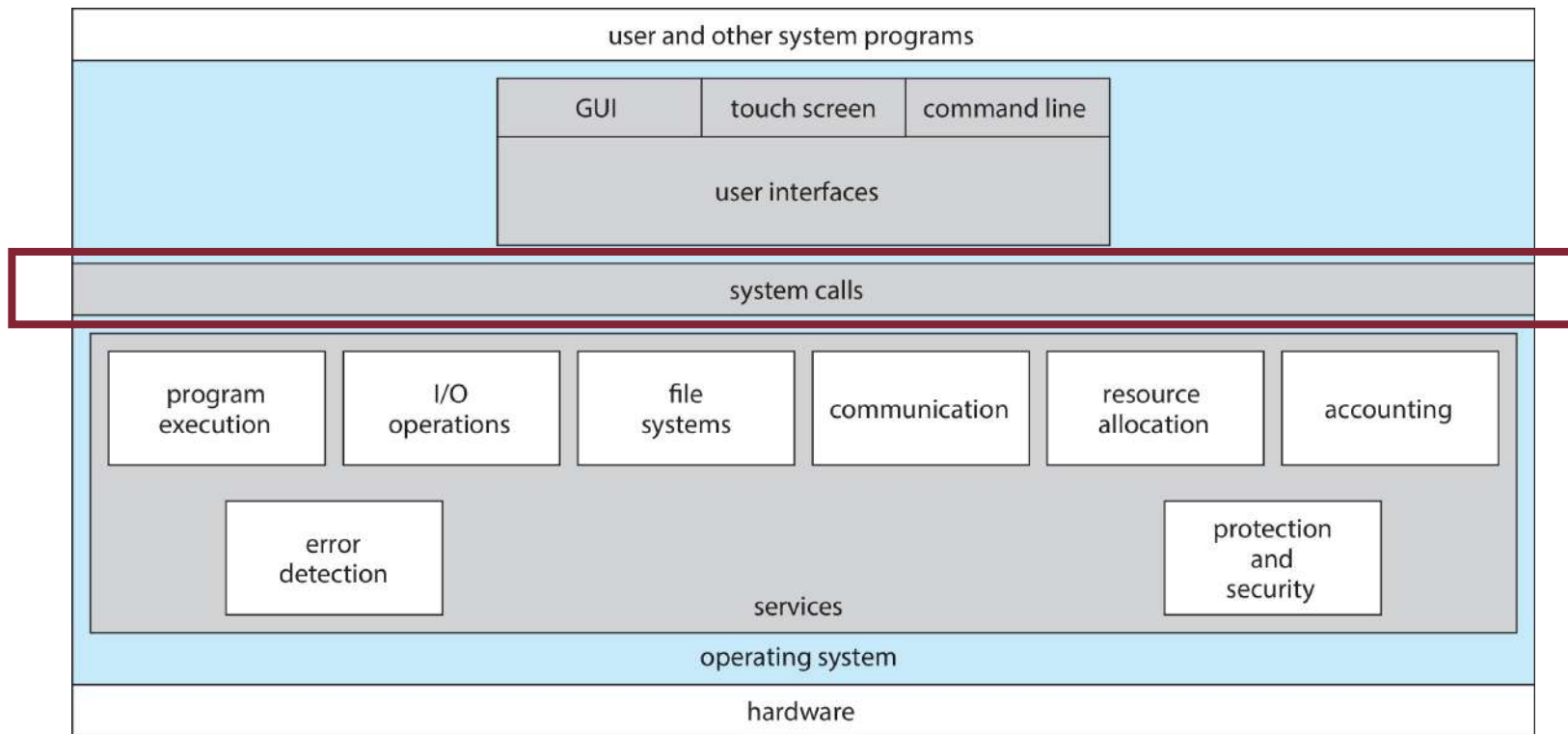
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User Programs-OS Interface



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- OS procedures that execute **privileged instructions** (e.g., I/O)
- Programming interface to the services provided by the OS
- Typically written in a high-level language (C or C++)
- Mostly accessed by programs via a high-level Application Programming Interface (API) rather than direct system call
 - GNU C Library (POSIX-based systems like UNIX, Linux, macOS)
 - Win32 API (Windows systems)
 - Java API (JVM)

System Calls: Categories

- 6 main categories of system calls:
 - Process control
 - File management
 - Device management
 - Information maintenance
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- When processes stop abnormally it may be necessary to provide core dumps and/or other diagnostic or recovery tools

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- The actual directory structure may be implemented using ordinary files on the file system, or through other means (more on this later)

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- Some systems represent devices as special files in the file system, so that accessing the "file" calls upon the appropriate OS device driver
 - e.g., the `/dev` directory on any UNIX system

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- Single step programs pausing execution after each instruction, and tracing the operation of programs (debugging)

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- Include create/delete communication connection, send/receive messages, transfer status information, and attach/detach remote devices

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- Include create/delete communication connection, send/receive messages, transfer status information, and attach/detach remote devices
- 2 models of communication:
 - message passing
 - shared memory

Communication: Message Passing

- The **message passing** model must support calls to:
 - Identify a remote process and/or host with which communicate to
 - Establish a connection between the two processes
 - Open and close the connection as needed
 - Transmit messages along the connection
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Simpler and easier (particularly for inter-computer communications) and generally appropriate for small amounts of data

Communication: Shared Memory

- The **shared memory** model must support calls to:
 - Create and access memory that is shared amongst processes (and threads)
 - Provide locking mechanisms restricting simultaneous access
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Faster and generally the better approach where large amounts of data are to be shared

Ideal when most processes need to read data rather than write

System Calls: Protection

- Provides mechanisms for controlling which users/processes have access to which system resources

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- System calls allow the access mechanisms to be adjusted as needed
- Non-privileged users may temporarily be granted elevated access permissions under specific circumstances
- Crucial in the age of ubiquitous network connectivity

The Anatomy of a System Call

System Call: **read** (C Library)

EXAMPLE OF STANDARD API

As an example of a standard API, consider the `read()` function that is available in UNIX and Linux systems. The API for this function is obtained from the `man` page by invoking the command

```
man read
```

on the command line. A description of this API appears below:

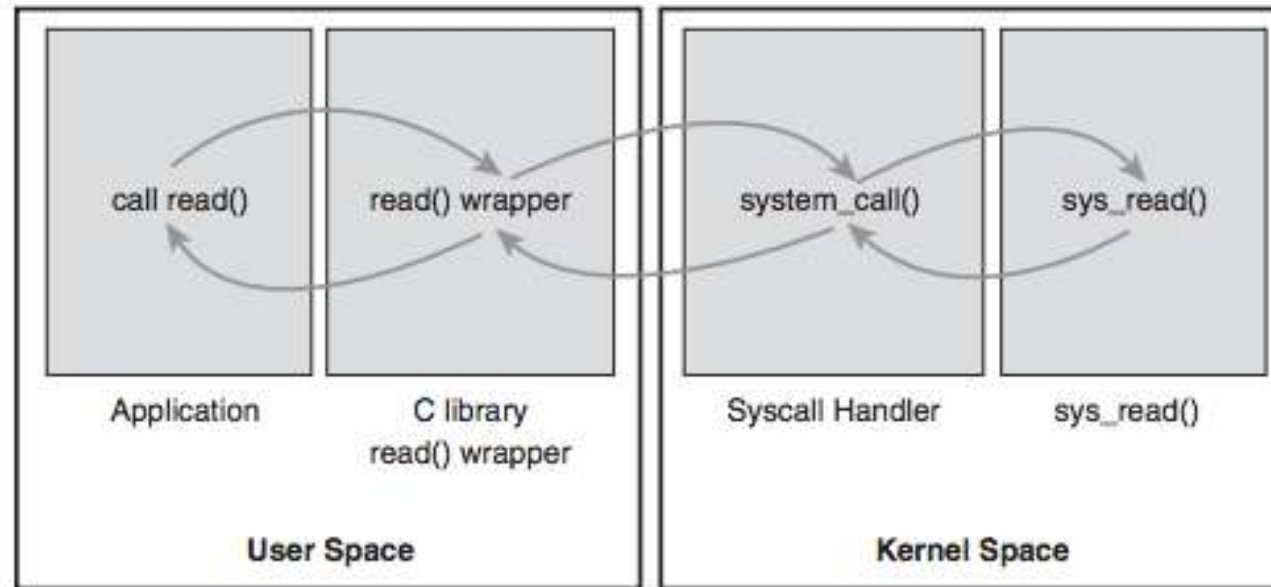
<code>#include <unistd.h></code>		
<code>ssize_t</code>	<code>read</code>	<code>(int fd, void *buf, size_t count)</code>
return value	function name	parameters

A program that uses the `read()` function must include the `unistd.h` header file, as this file defines the `ssize_t` and `size_t` data types (among other things). The parameters passed to `read()` are as follows:

- `int fd`—the file descriptor to be read
- `void *buf`—a buffer into which the data will be read
- `size_t count`—the maximum number of bytes to be read into the buffer

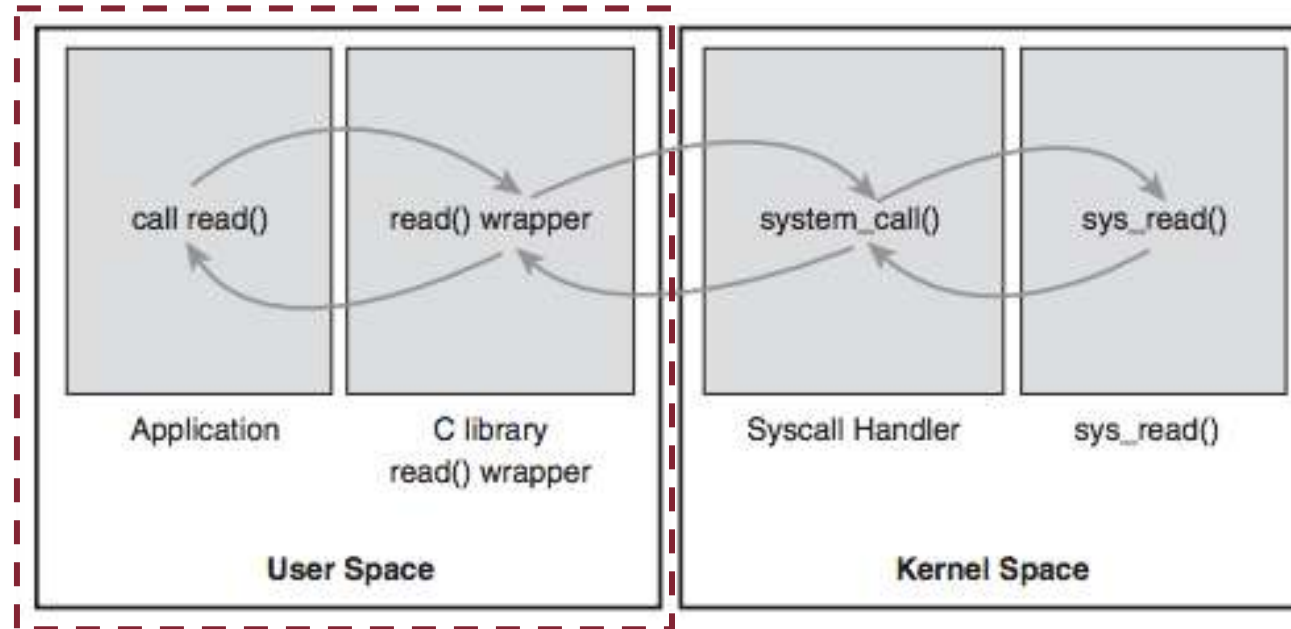
On a successful read, the number of bytes read is returned. A return value of 0 indicates end of file. If an error occurs, `read()` returns `-1`.

System Call: Flow



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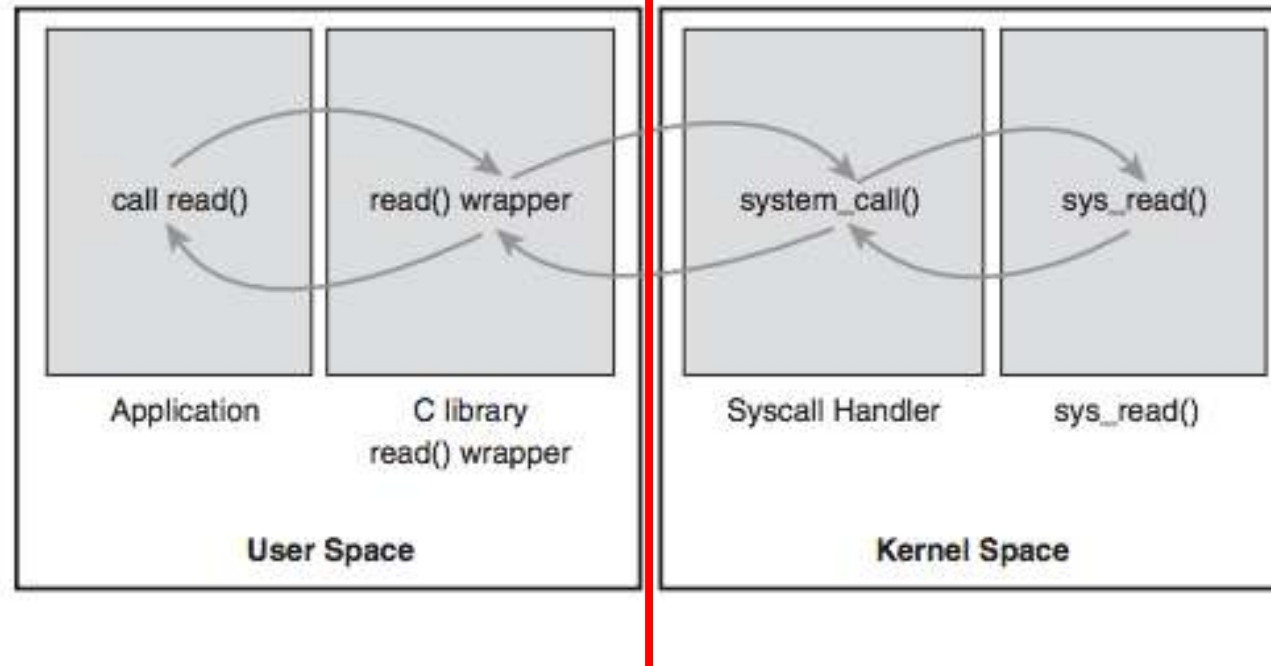
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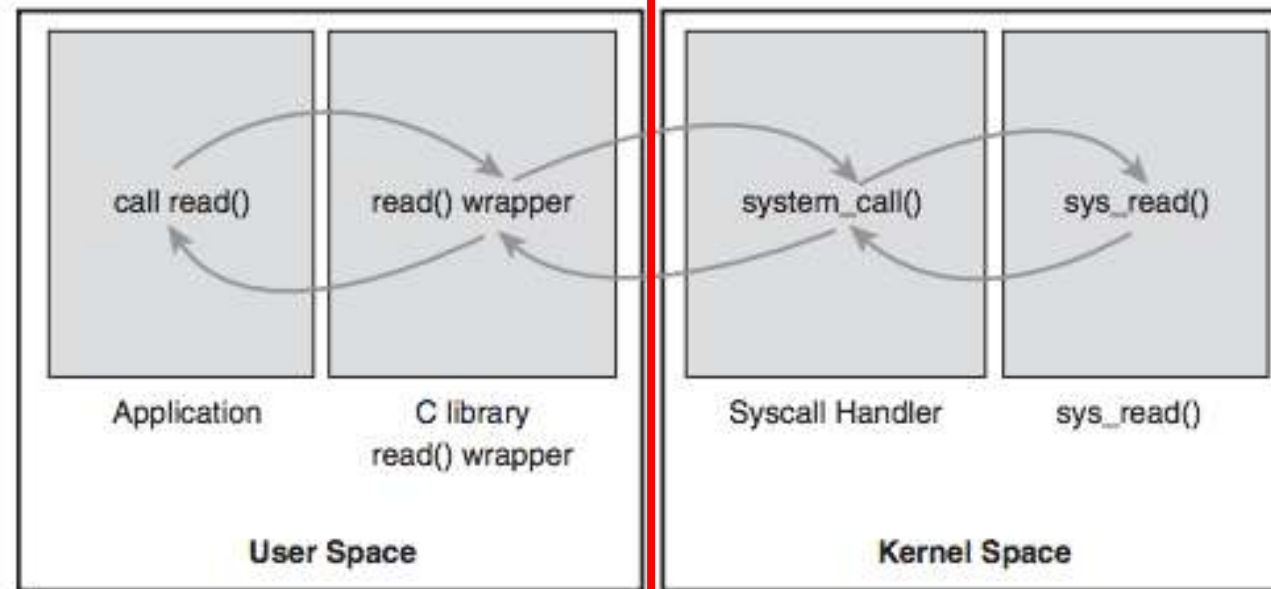
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System Call: Flow

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Most of the details are hidden by the API



The caller must only obey to the API
(know the input arguments and the expected output from the OS)

System Call Example: Reading from File

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int main() {  
    ...  
    int nRead = read(fd, buf, count);  
    ...  
}
```

C library's **read** function call

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MOV %eax, $sys_read  
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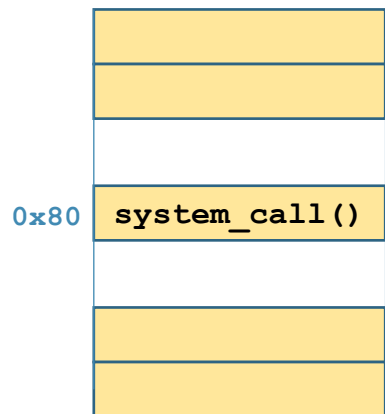
store the number which uniquely identifies the system call requested

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A **trap** jumps to the
interrupt vector table (IVT)
in the OS kernel

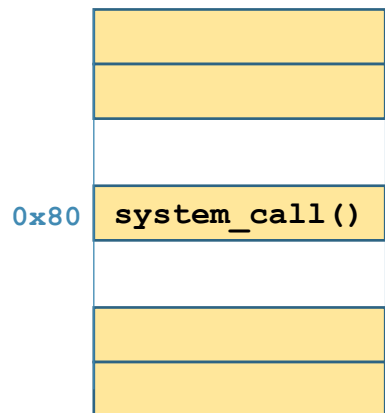


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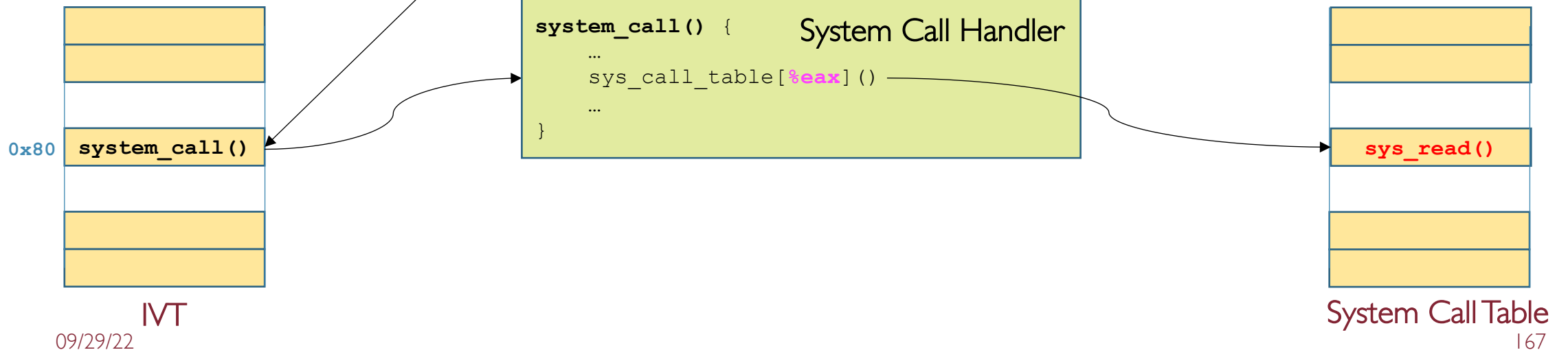
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```
system_call() {      System Call Handler  
    ...  
    sys_call_table[%eax]()  
    ...  
}
```

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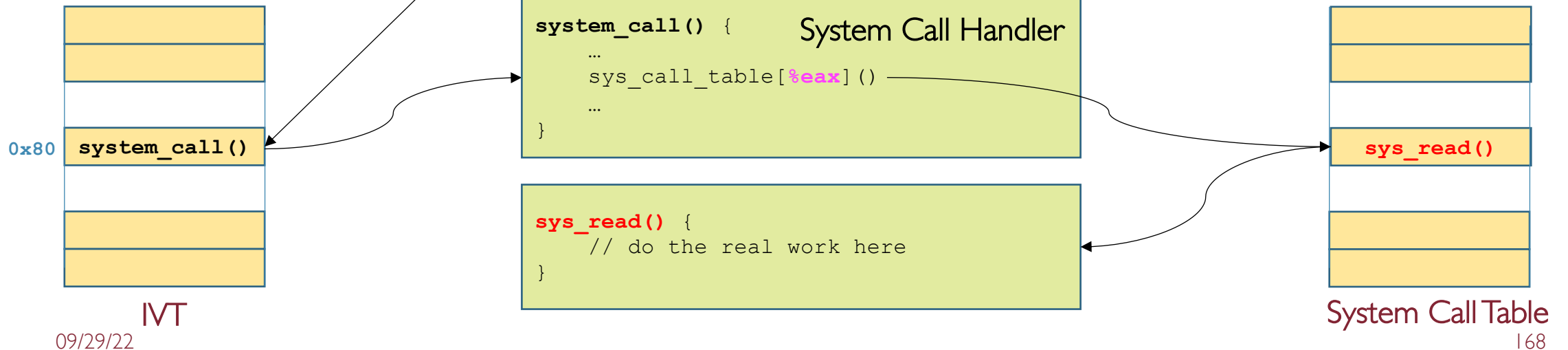
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- The **system call handler** is responsible for:
 - saving the status of user-mode computation on dedicated registers
 - finding and jumping to the correct routine for that trap (e.g., **sys_read()**)
 - restoring user-mode program's state upon the service routine is done (e.g., **IRET** privileged instruction)

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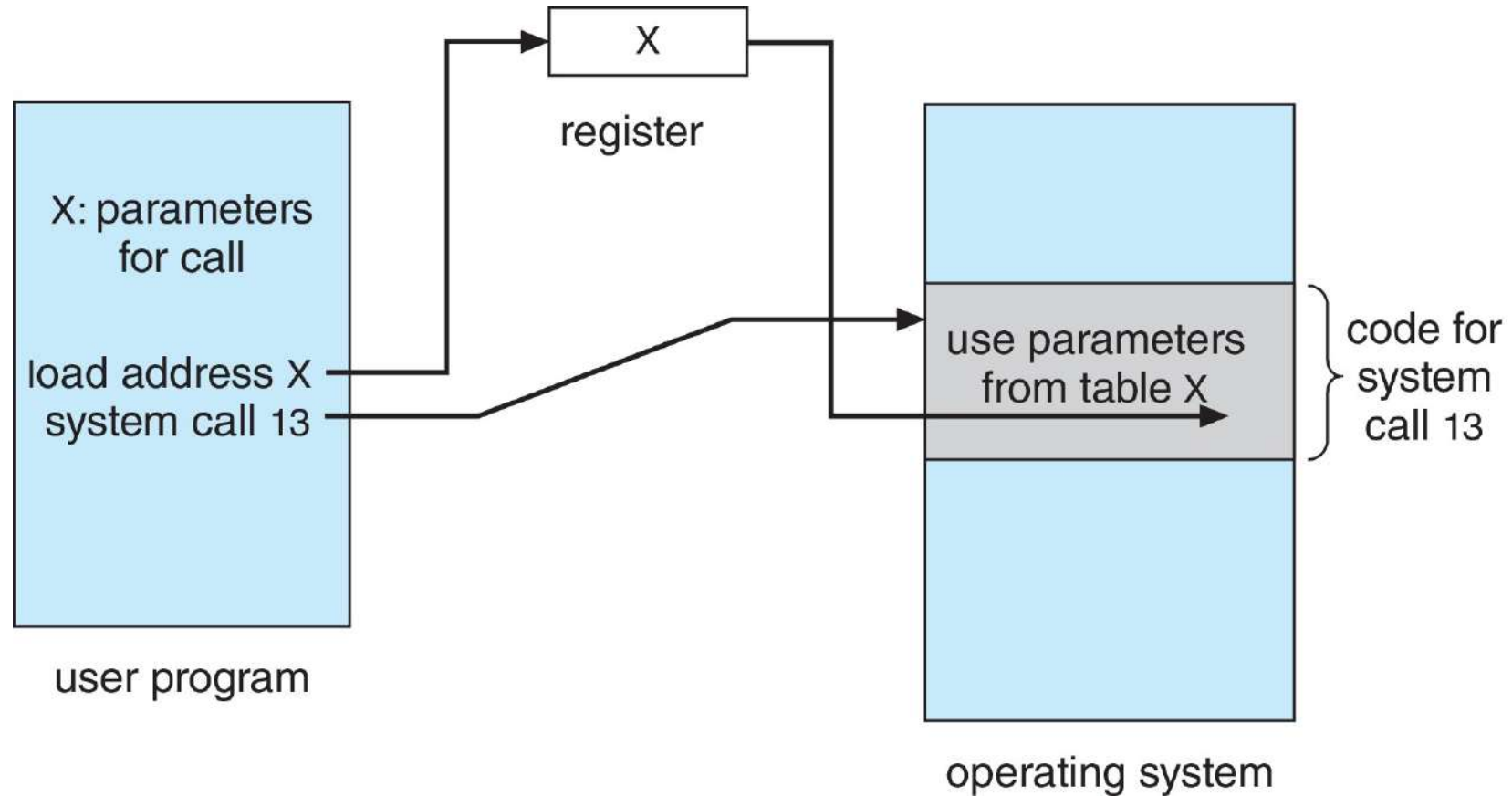
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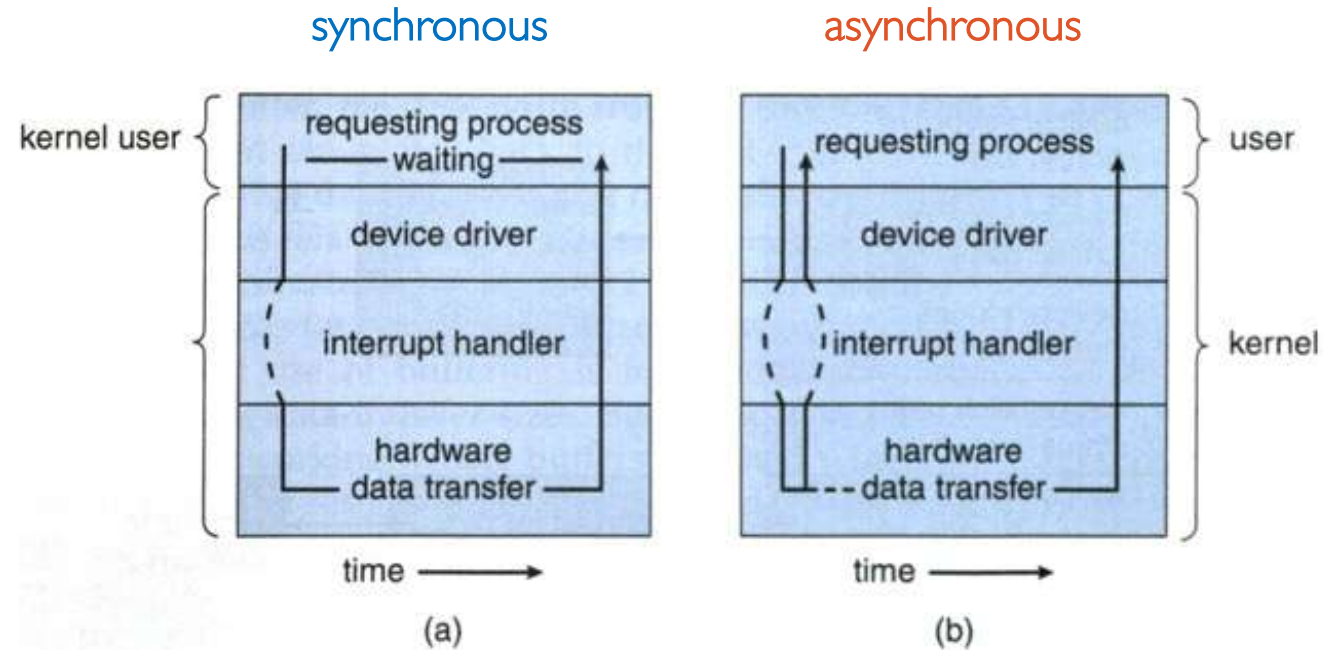
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Block and stack methods do not limit the number or length of parameters being passed

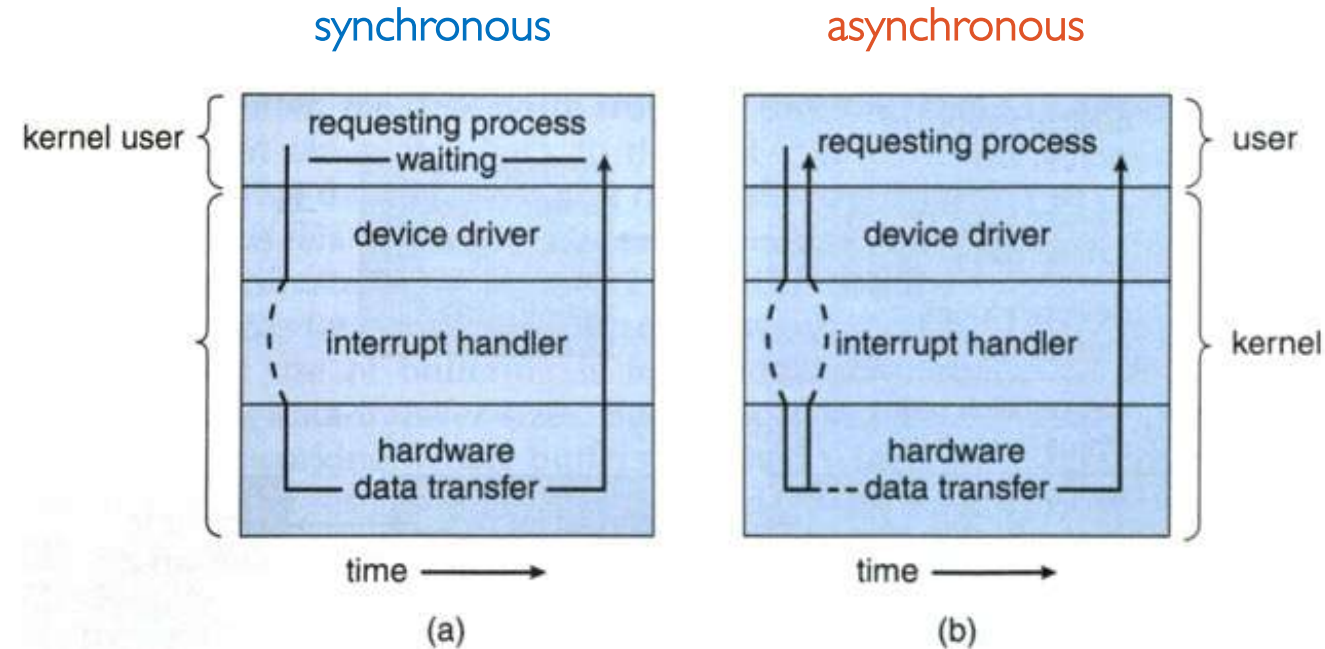
Parameter Passing via Table



Blocking vs. Non-Blocking I/O



Blocking vs. Non-Blocking I/O



NOTE

In a multi-programming and multi-tasking system, blocking I/O will not leave the CPU idle until I/O task is completed!
In fact, the CPU will schedule another (ready) process to take over

System Calls: Windows vs. UNIX APIs

EXAMPLES OF WINDOWS AND UNIX SYSTEM CALLS

The following illustrates various equivalent system calls for Windows and UNIX operating systems.

	Windows	Unix
Process control	CreateProcess() ExitProcess() WaitForSingleObject()	fork() exit() wait()
File management	CreateFile() ReadFile() WriteFile() CloseHandle()	open() read() write() close()
Device management	SetConsoleMode() ReadConsole() WriteConsole()	ioctl() read() write()
Information maintenance	GetCurrentProcessID() SetTimer() Sleep()	getpid() alarm() sleep()
Communications	CreatePipe() CreateFileMapping() MapViewOfFile()	pipe() shm_open() mmap()
Protection	SetFileSecurity() InitializeSecurityDescriptor() SetSecurityDescriptorGroup()	chmod() umask() chown()

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- In multi-tasking systems, allows the CPU not to be monopolized by "selfish" processes
- The timer generates an interrupt every, say, 100 microseconds
- At each timer interrupt, the CPU scheduler takes over and decides which process to execute next

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- Interrupts may occur at any time and interfere with running processes
- OS must be able to synchronize the activities of cooperating, concurrent processes
- Hardware must ensure that short sequences of instructions (e.g., read-modify-write) are executed **atomically** by either:
 - Disabling interrupts before the sequence and re-enable them afterwards
 - or
 - Special instructions that are natively executed atomically

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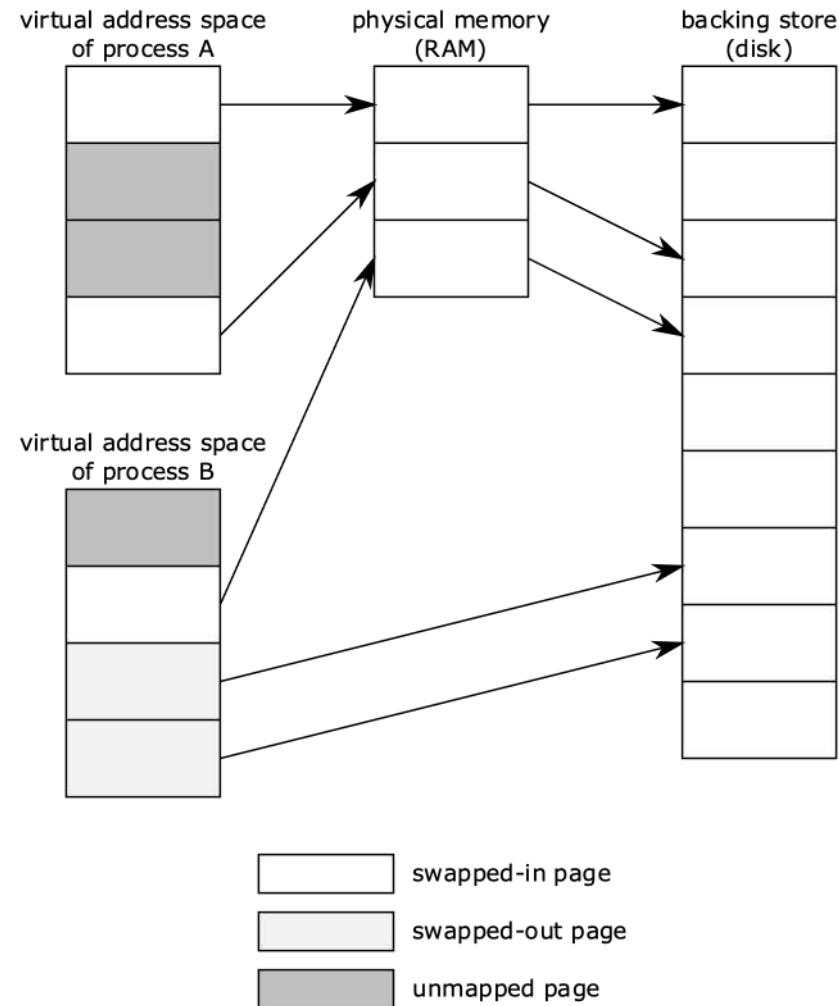
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 - They are entirely loaded in virtual memory, though!
- Implemented both in HW (**MMU**) and SW (**OS**)
 - **MMU** is responsible for translating virtual addresses into physical ones
 - **OS** is responsible for managing virtual address spaces

Virtual vs. Physical Address Space

- On a 64 bit system the CPU is able to address 2^{64} bytes = 16 exbibytes (EiB)
- Virtual address space ranges from 0 to $2^{64} - 1$
- This is about a billion times more than main memory capacity currently available!
- Virtual address space is typically divided into contiguous blocks of the same size (e.g., 4 KiB), called **pages**
- Pages which are not loaded in main memory are stored on disk

Virtual vs. Physical Address Space



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- The OS must be aware of which pages are loaded in main memory and which ones are on disk

Outline of this Lecture

1. Computer architecture review
2. HW support for OS functionalities and services
3. OS design and implementation

Design Goals

- The internal structure of different OSs can vary widely

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- **User** vs. **System** goals
 - easy to use vs. easy to design/implement

Design Goals

- The internal structure of different OSs can vary widely
- **User** vs. **System** goals
 - easy to use vs. easy to design/implement
- It is crucial to separate policies from mechanisms
 - **policy** → *what* will be done
 - **mechanism** → *how* to do it

Policy vs. Mechanism

- Decoupling policy logic from the underlying mechanism is a general design principle in computer science, as it improves system's:
 - **flexibility** → addition and modification of policies can be easily supported
 - **reusability** → existing mechanisms can be reused for implementing new policies
 - **stability** → adding a new policy doesn't necessarily destabilize the system

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- Early OSs developed in assembly language,
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 - **PRO** → direct control over the HW (high efficiency)
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- Today, a mixture of languages:
 - Lowest levels in assembly
 - Main body in C
 - Systems programs in C, C++, scripting languages like PERL, Python, etc.

OS Structure

- OS should be partitioned into separate subsystems, each with carefully defined tasks, inputs, outputs, and performance characteristics

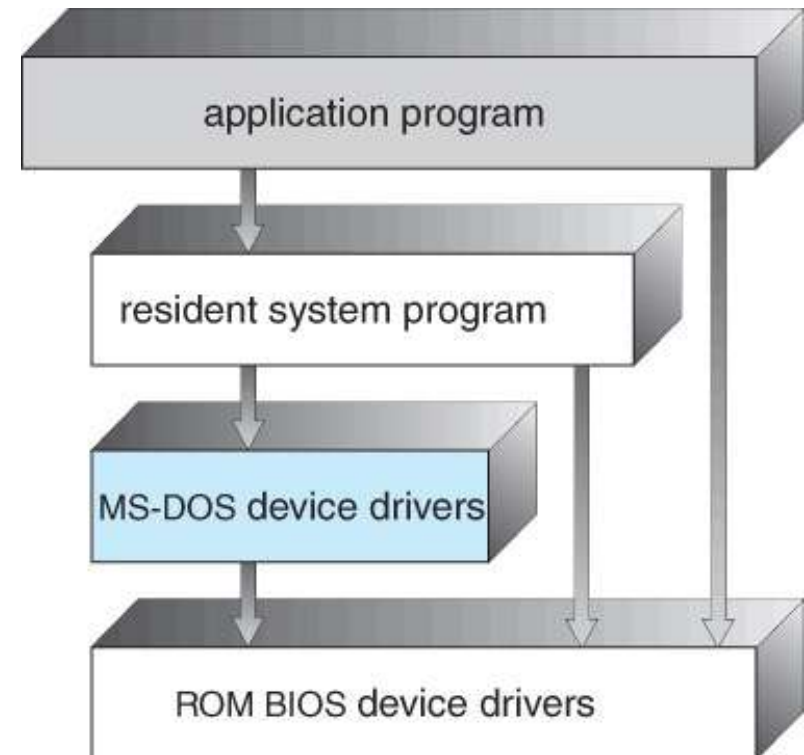
OS Structure

- OS should be partitioned into separate subsystems, each with carefully defined tasks, inputs, outputs, and performance characteristics
- Various ways to structure an operating system:
 - Simple → MS-DOS
 - Complex → UNIX
 - Layered → MULTICS
 - Microkernel → Mach

MS-DOS Structure: Simple Structure

No modular subsystems at all!

No separation between
user and kernel mode



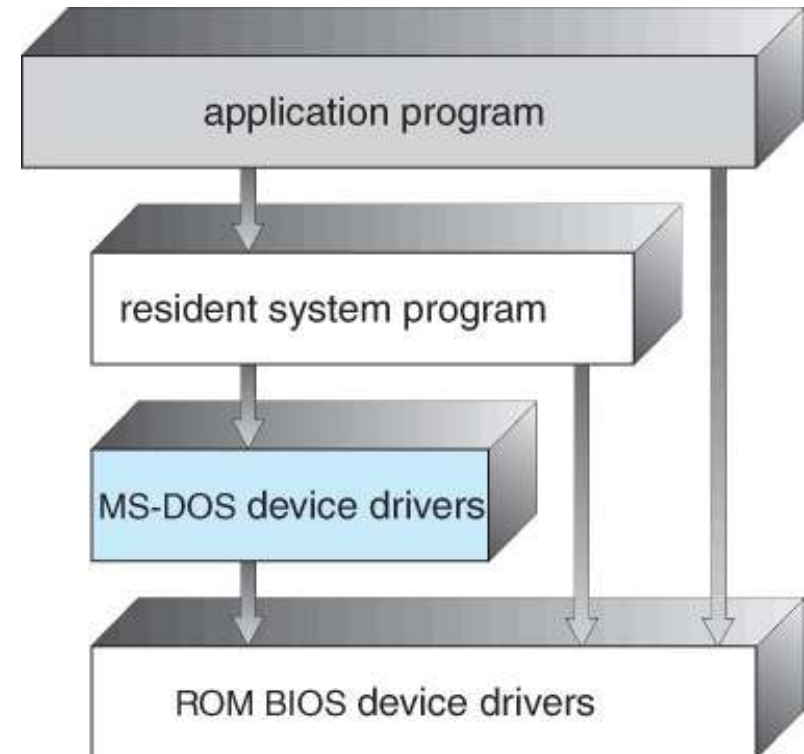
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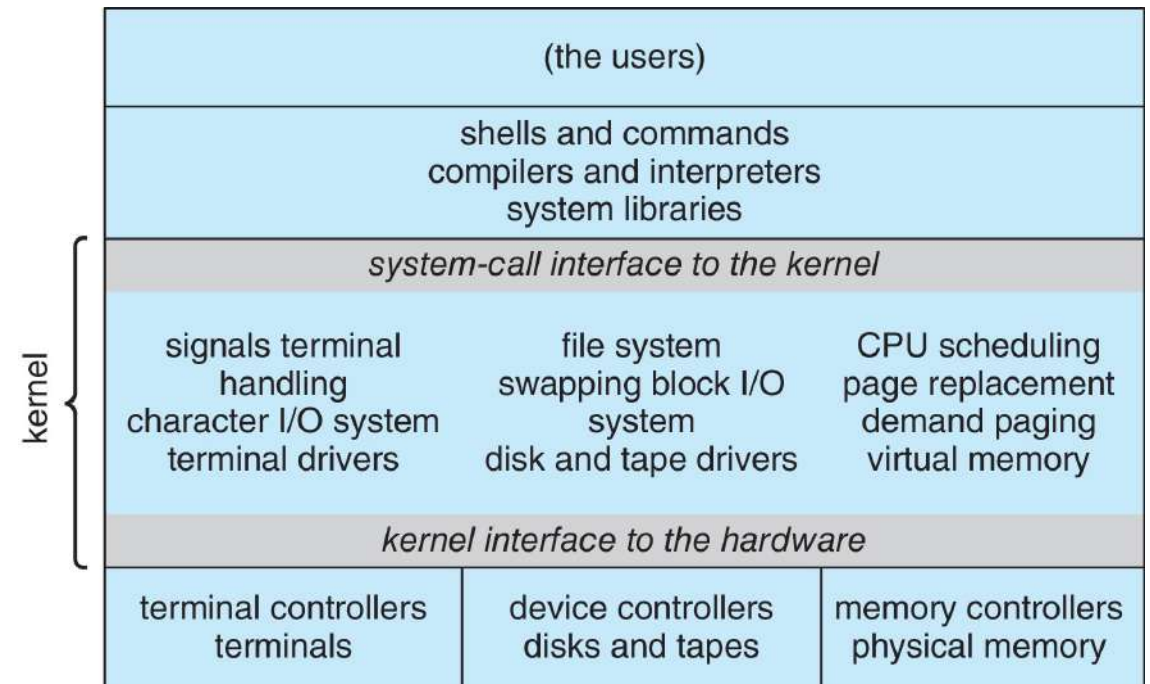
CONs: rigidity, security



UNIX Structure: Traditional Monolithic Kernel

Essentially, one huge piece of software with all services living in the same address space as one big process

Most of modern OSs are variant of this traditional monolithic structure



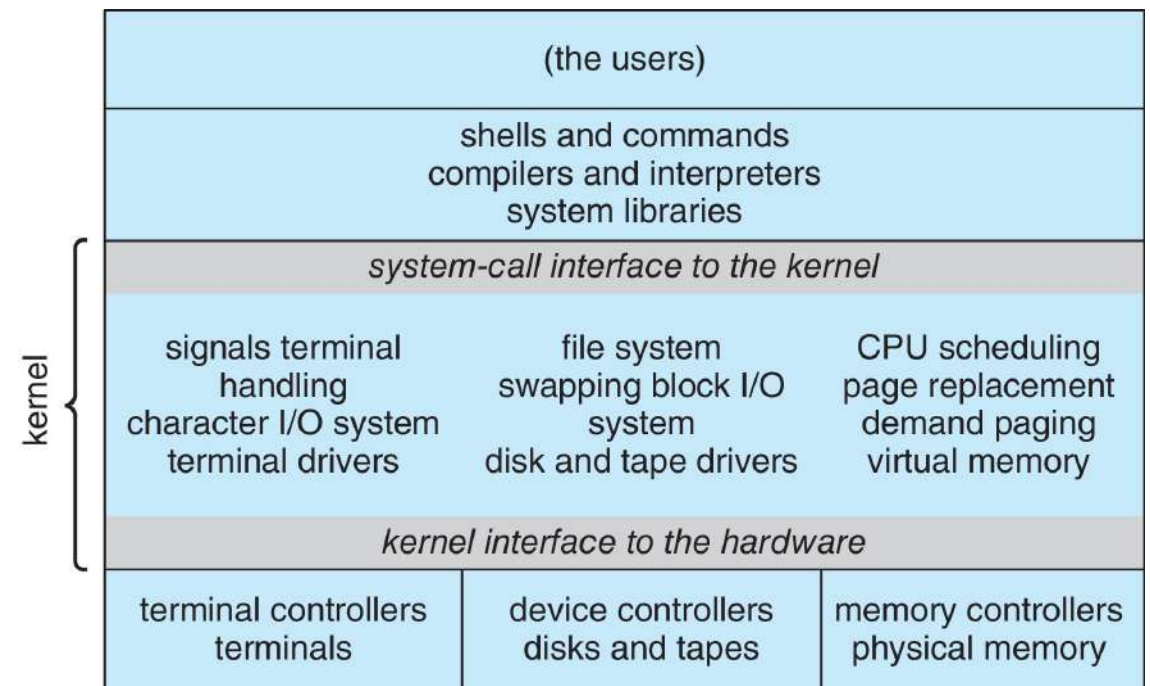
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PROs: efficiency, easy to implement

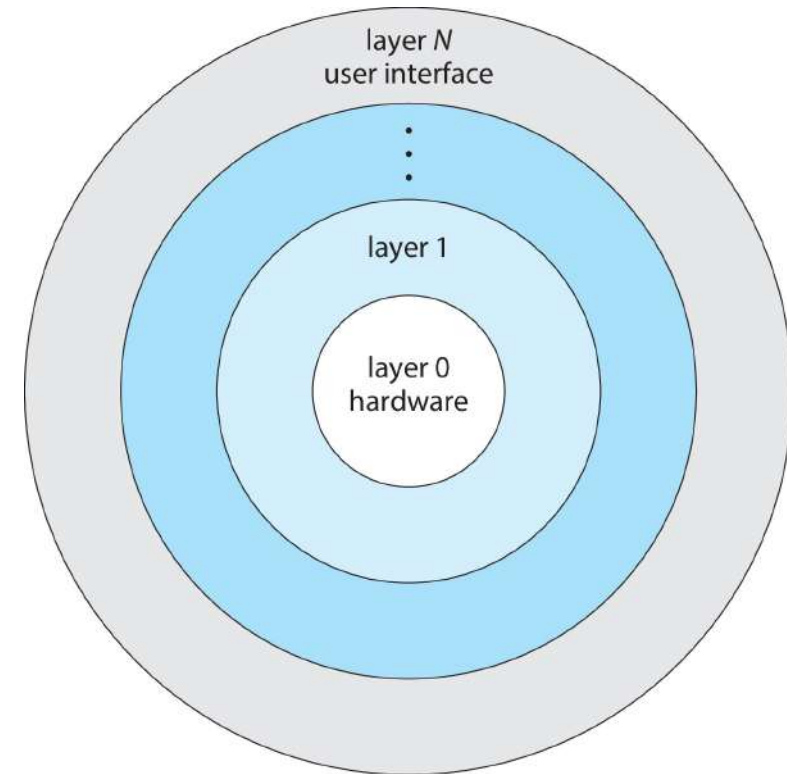
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Layered Structure

The OS is divided into N layers
(HW = layer 0)

Each layer L uses the functionalities
implemented by the layer $L-1$ to expose
new functionalities to layer $L+1$



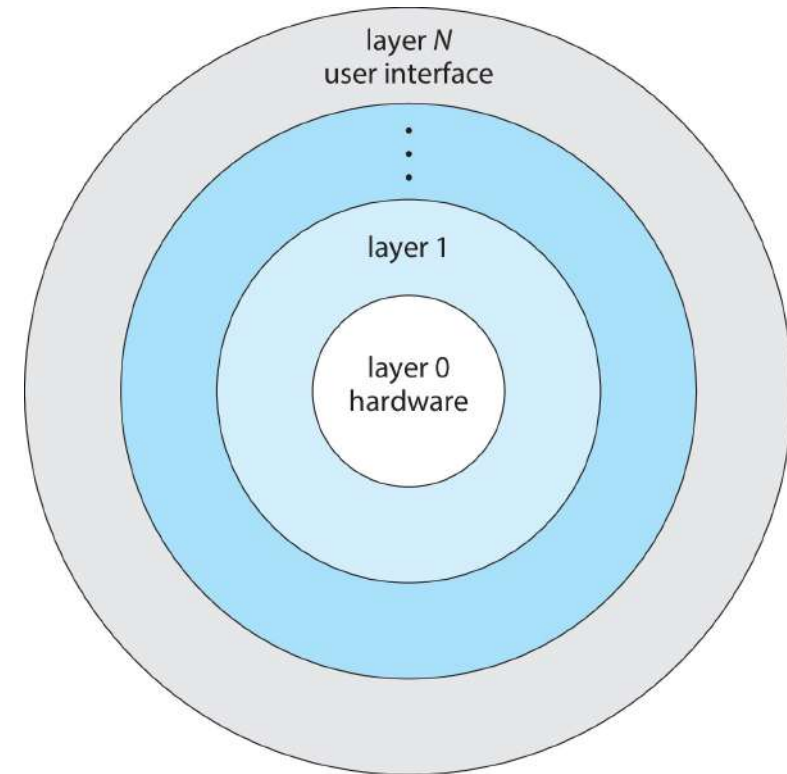
Layered Structure

The OS is divided into N layers
(HW = layer 0)

Each layer L uses the functionalities
implemented by the layer $L-1$ to expose
new functionalities to layer $L+1$

PROs: modularity, portability, easy to debug

CONs: communication overhead, extra copy

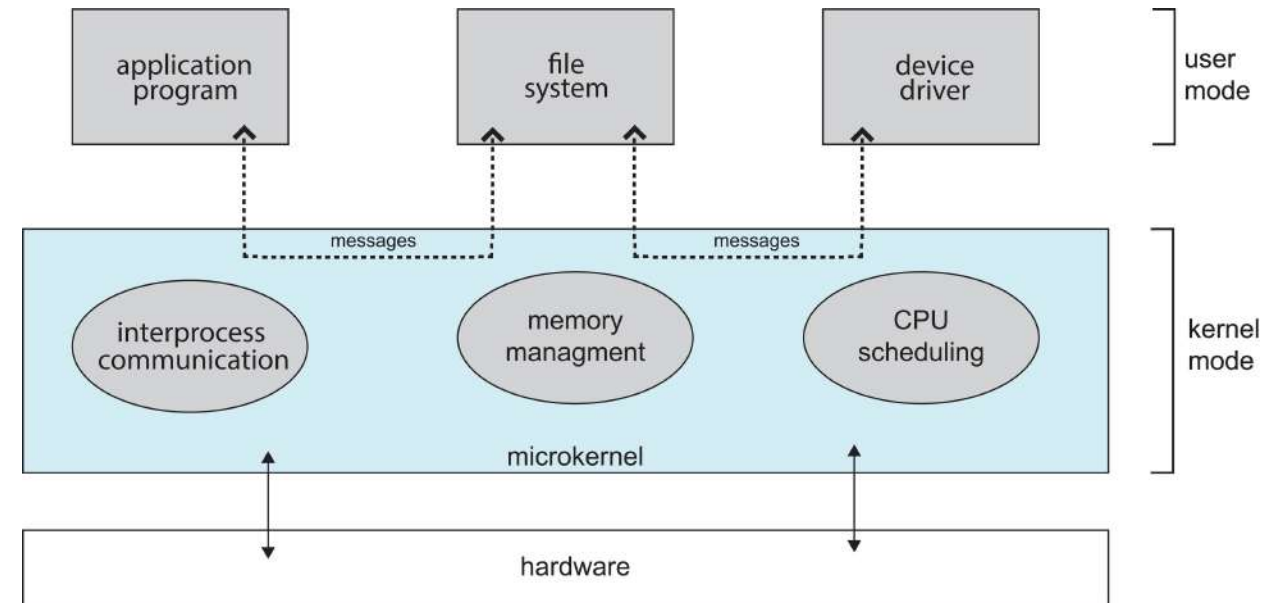


Microkernel Structure

The opposite approach of monolithic

The kernel just contains very basic functionalities, everything else which is still logically part of the OS runs in user mode

Policy (user mode) vs. mechanism (microkernel) separation



Microkernel Structure

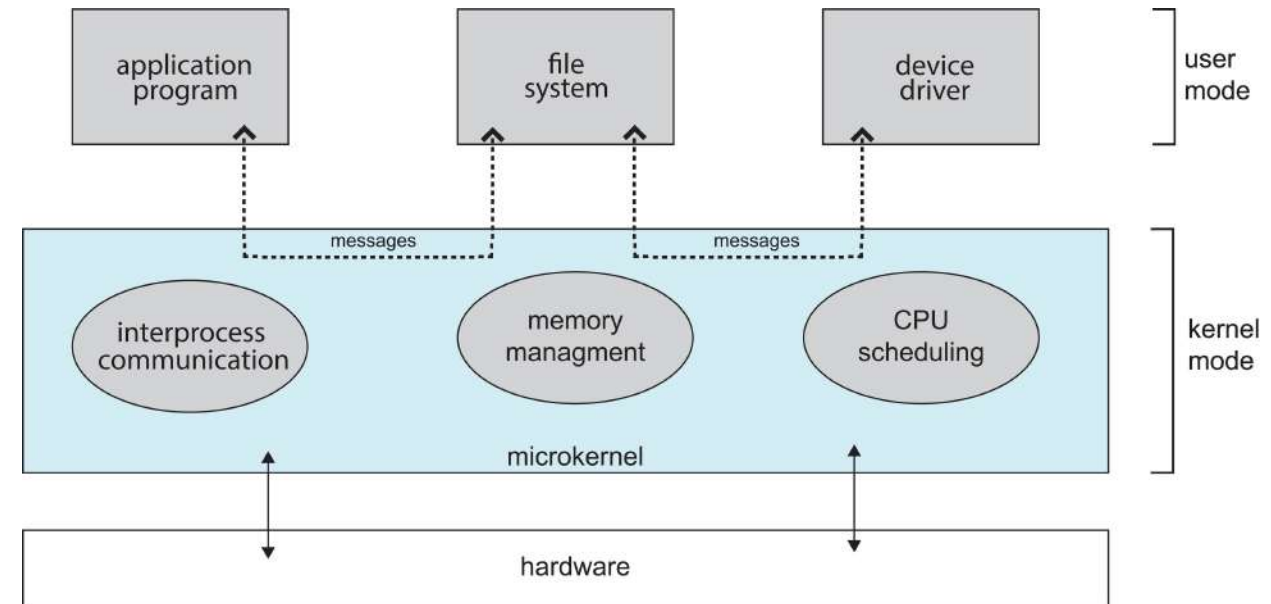
The opposite approach of monolithic

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Policy (user mode) vs. mechanism (microkernel) separation

PROs: security, reliability, extendibility

CONs: efficiency (message passing)



Loadable Kernel Modules (LKMs)

- Many modern OSs use loadable kernel modules (LKMs)
 - Uses object-oriented approach
 - Each core component is separate
 - Each talks to the others over known interfaces
 - Each is loadable as needed within the kernel (i.e., in kernel space)
- Similar to layered structure but more flexible

Monolithic vs. Microkernel: Hybrid Trade-off

- Try to get the best out of both approaches
 - combining multiple approaches to address performance, security, usability needs
- Linux and Solaris: monolithic + LKMs (i.e., modular monolithic)
- Windows NT: mostly monolithic + microkernel for different subsystems
- Apple Mac OS X: monolithic (BSD UNIX) + microkernel (Mach) + LKMs

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- Most of the services provided by the OS to the applications rely on specific HW features
- The OS is tightly coupled to the HW of the host machine
- Several approaches to OS design and implementation
- **Advice:** Keep your Computer Architecture book at hand!